

# Neutrinoless double beta decay in effective field theory

Uncovering the Mechanism of  $0\nu\beta\beta$

Wouter Dekens

with

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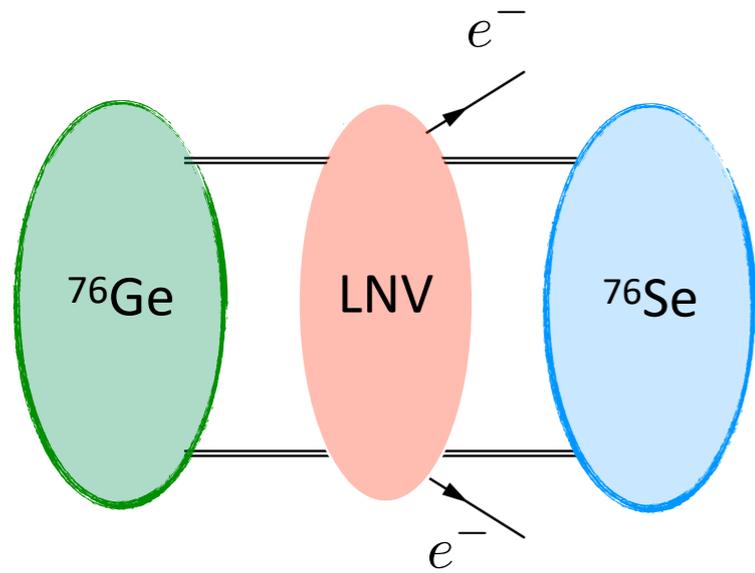
Based on:

arXiv:2002.07182 , 1907.11254 ,1806.02780, 1710.01729,  
1802.10097, 1710.05026, 1708.09390

UC San Diego

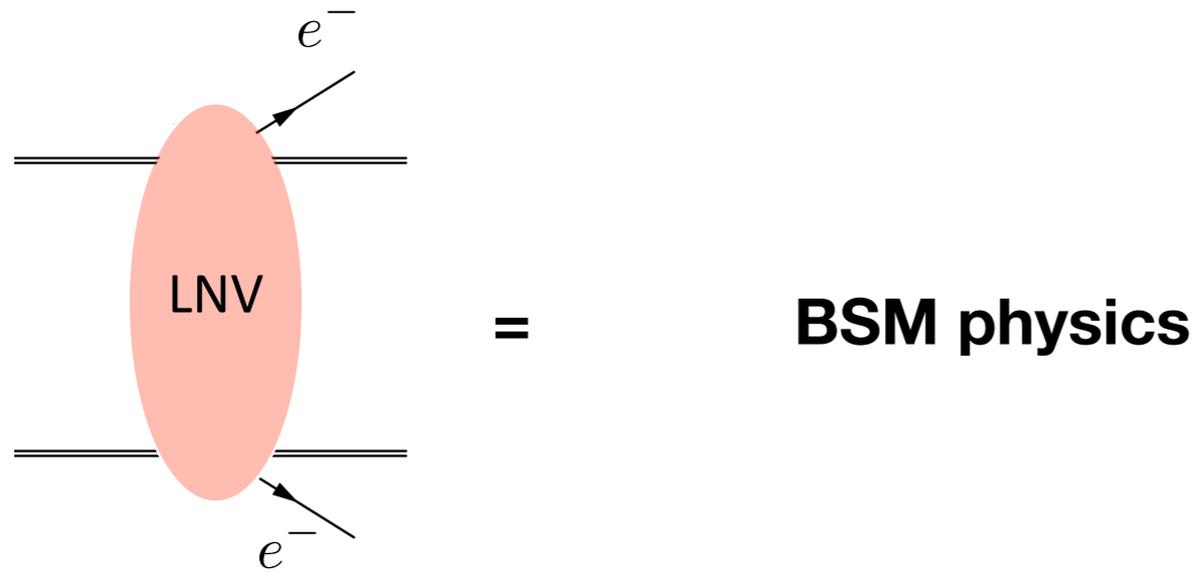
# Introduction

$0\nu\beta\beta$



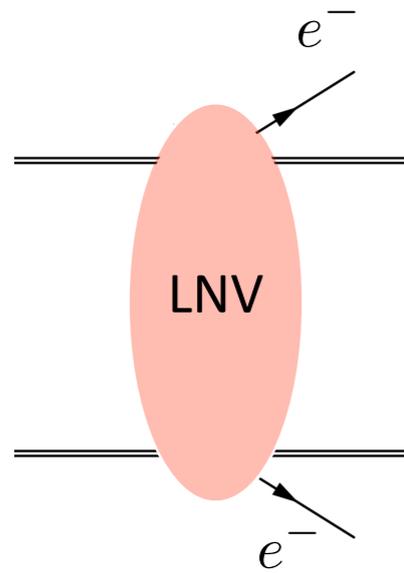
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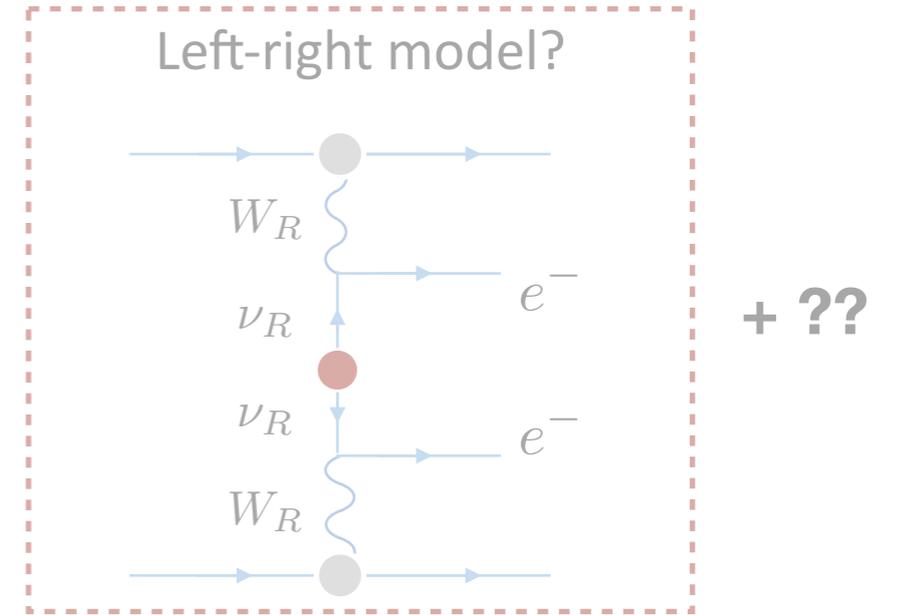
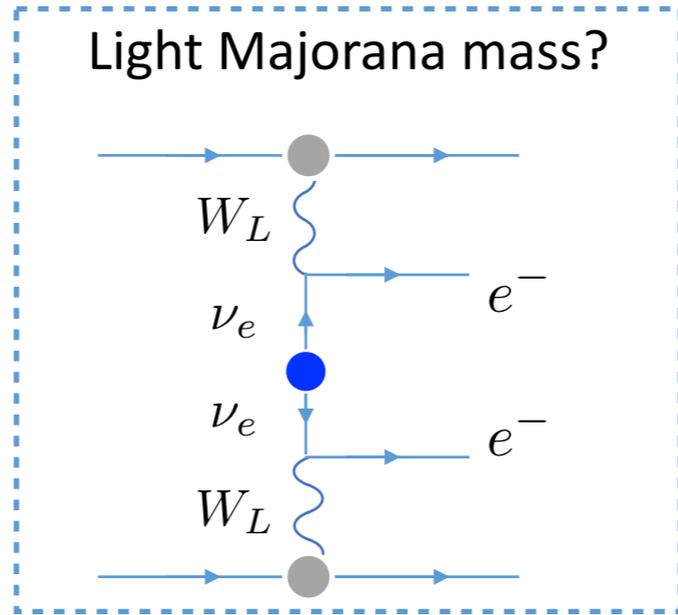


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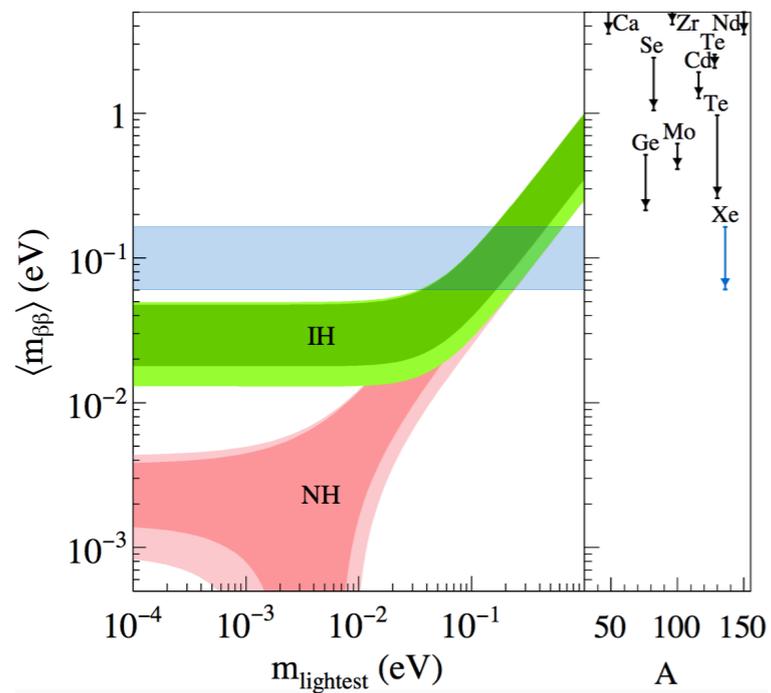
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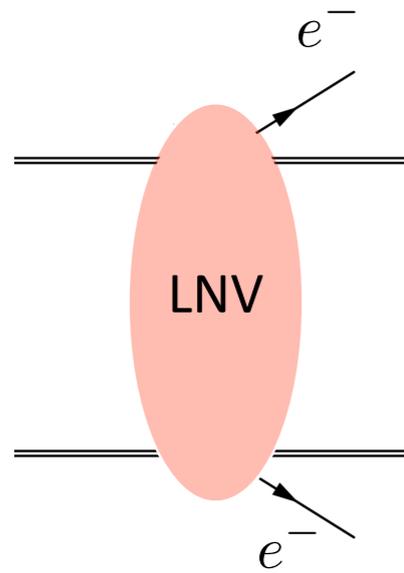


## Well-known Majorana mass mechanism

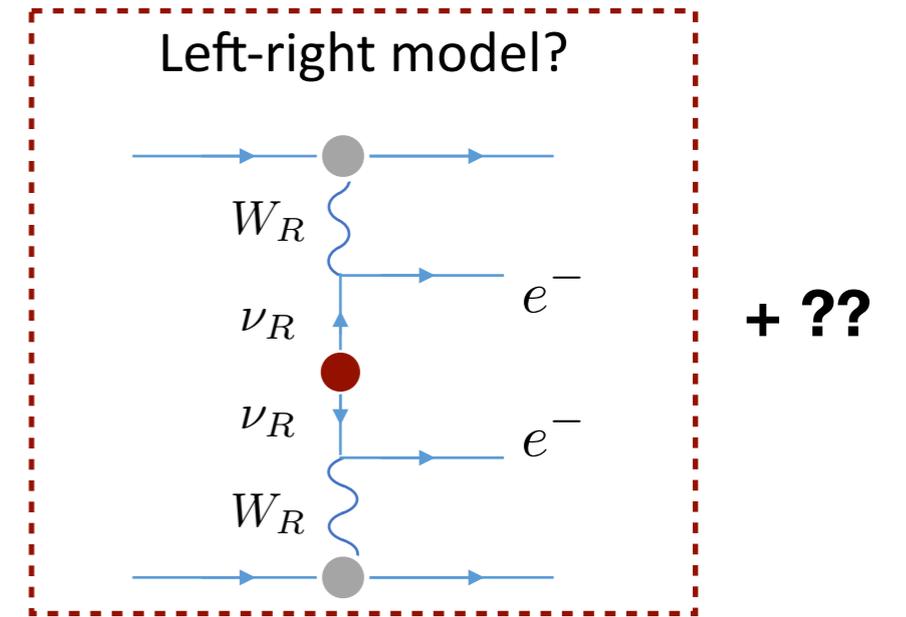
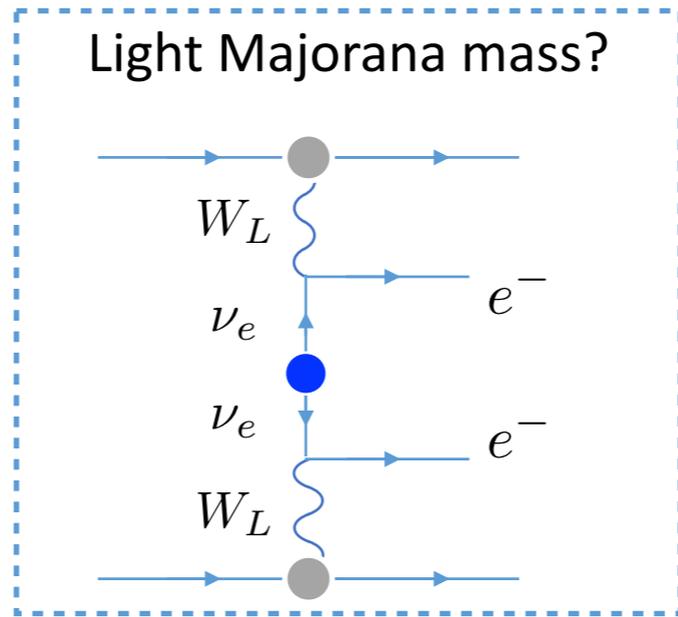


- Implications for the mass hierarchy

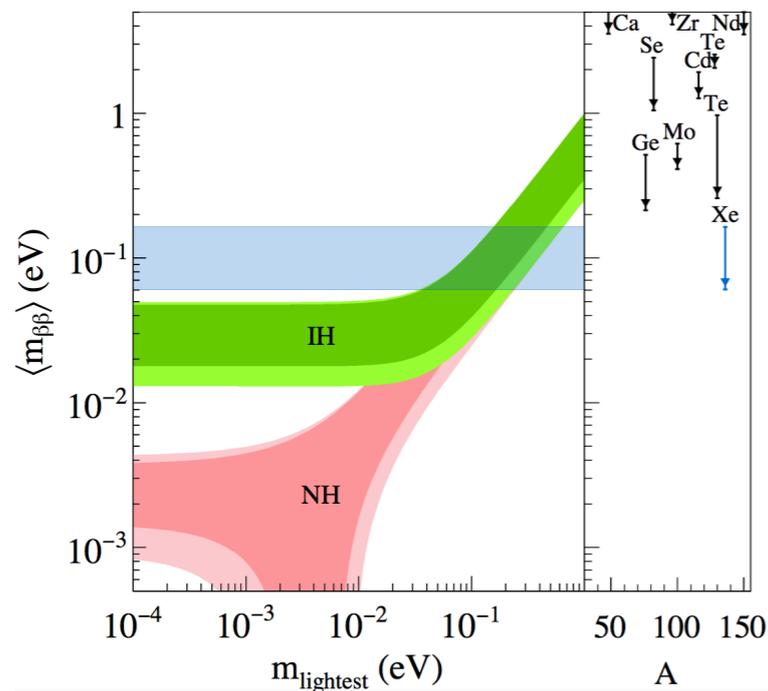
## $0\nu\beta\beta$



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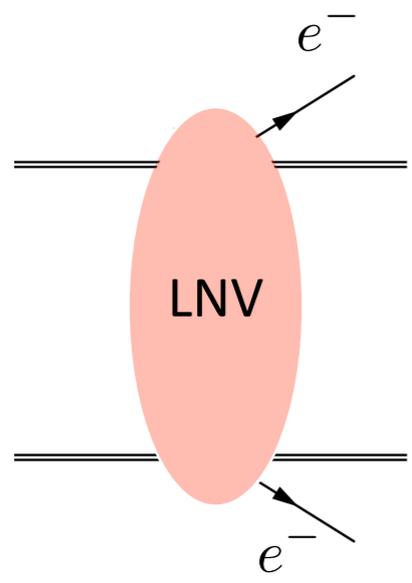


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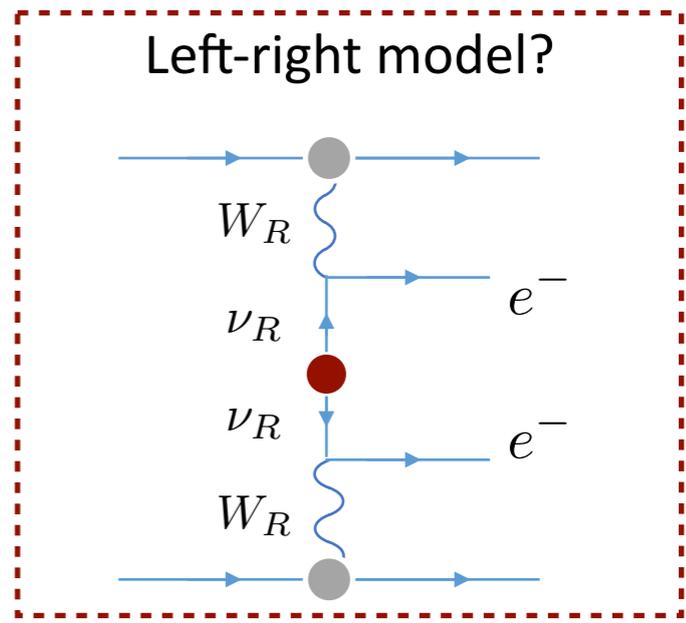
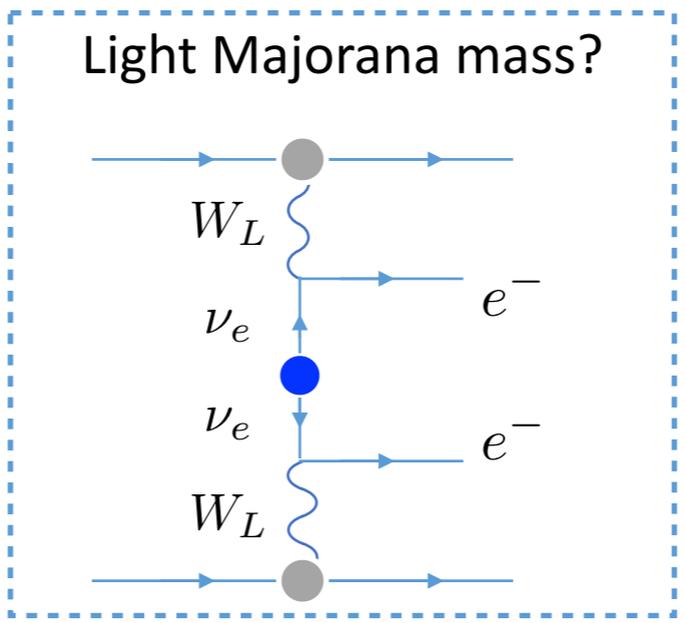
## Heavy BSM mechanisms

- Many possible scenarios
  - Left-right model,
  - R-parity violating SUSY
  - Leptoquarks...

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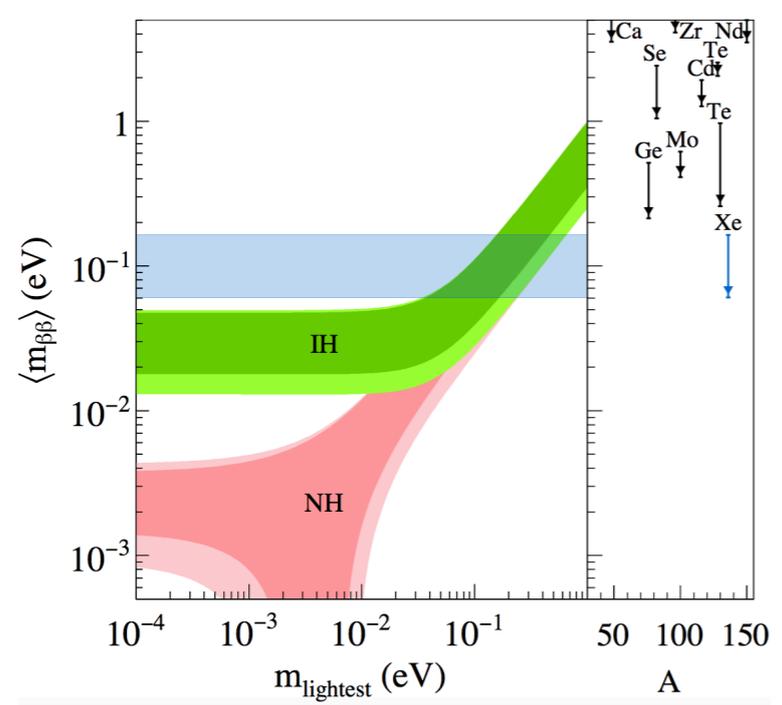


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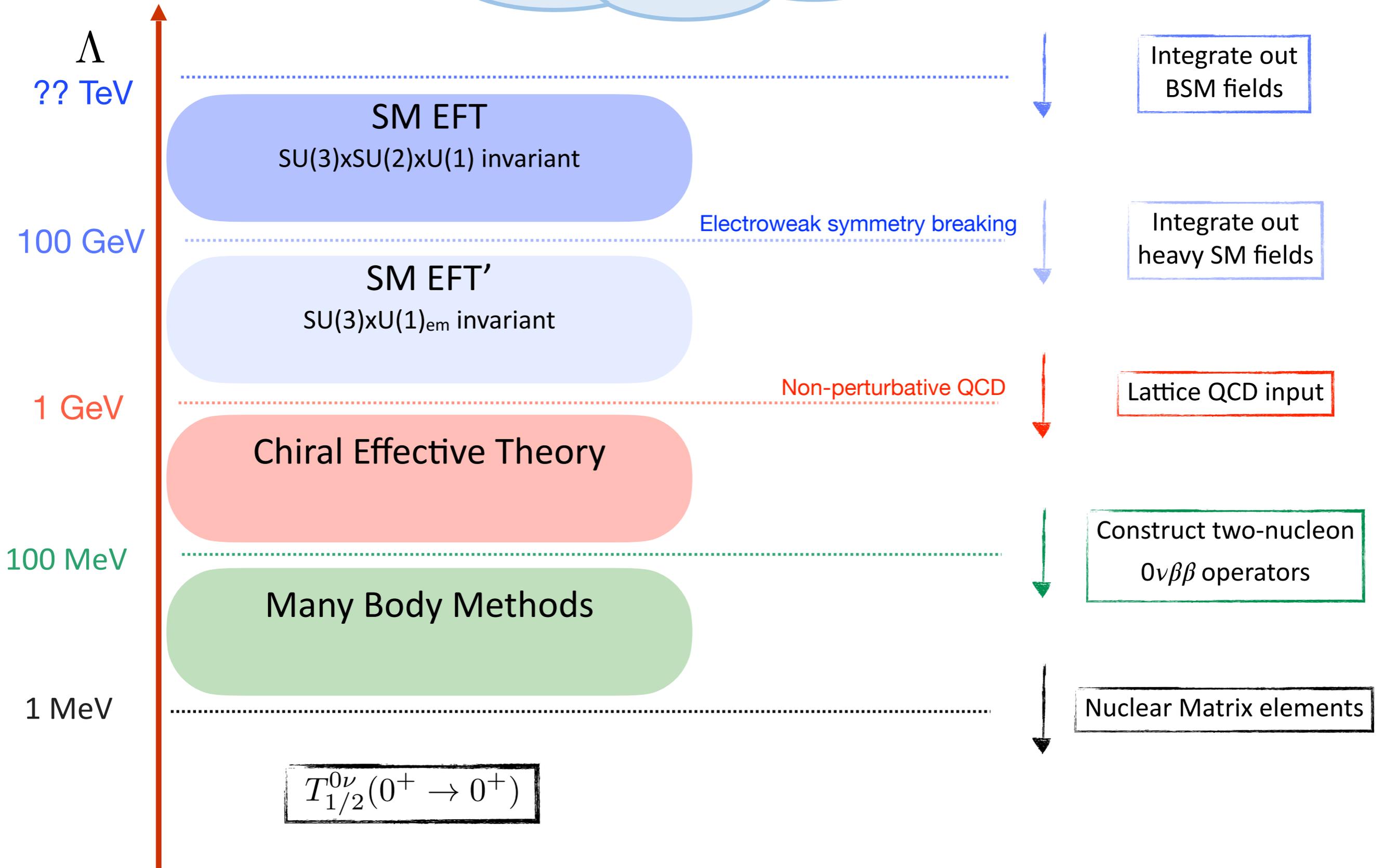
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### Heavy BSM mechanisms

- Many possible scenarios
  - Left-right model,
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  - Leptoquarks...
- How to describe all LNV sources systematically?

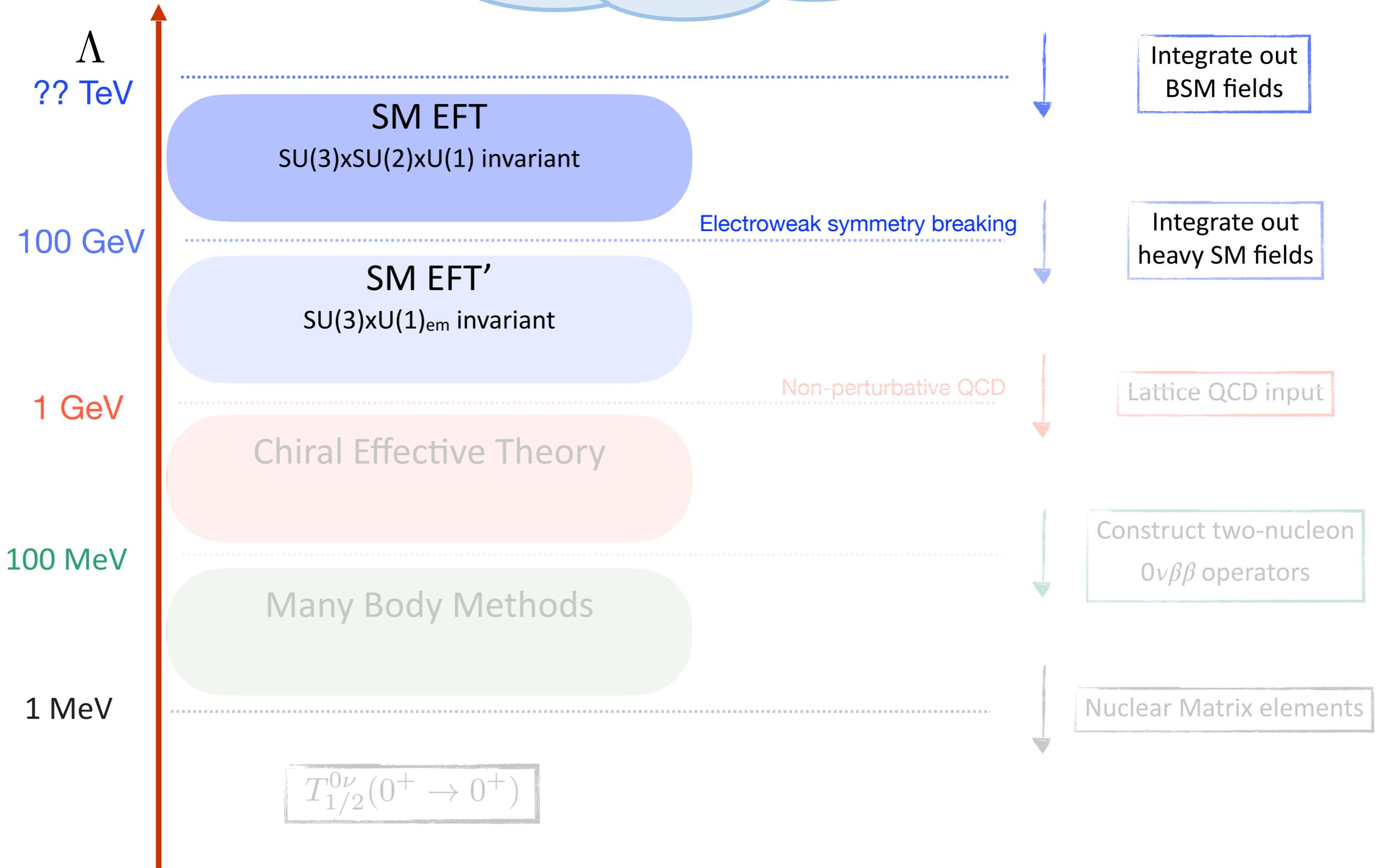
# Outline

Lepton-number violation:  
seesaw, left-right model, leptoquarks,...



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# Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)} + \frac{c_i^{(9)}}{\Lambda^5} O_i^{(9)} + \dots$$

## Dimension-five

$$\mathcal{L}_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H})(\tilde{H}^T L)$$

## Dimension-seven

- 12  $\Delta L=2$  operators

	1 : $\psi^2 H^4 + \text{h.c.}$
$\mathcal{O}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L^i C L^m) H^j H^n (H^\dagger H)$
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- Subset of operators constructed

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- Recently complete basis

Liao and Ma '20; Li et al '20;

# Effective Field Theory

Naive scaling of Dimension 5, 7, 9 operators

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{c_5}{\Lambda} \left[ 1 + \left(\frac{v}{\Lambda}\right)^2 \frac{c_7}{c_5} + \left(\frac{v}{\Lambda}\right)^4 \frac{c_9}{c_5} \right]$$

- $v/\Lambda \ll 1$  So why keep dimension 7 & 9?

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$m_\nu \sim c_5 v^2 / \Lambda$  Allows for relative enhancement:

- $c_5 \ll O(1)$ ,  $\Lambda = \mathcal{O}(1 - 100)\text{TeV}$ 
  - Relative enhancement of higher-dimensional terms due to
- Happens, for example, in the left-right model

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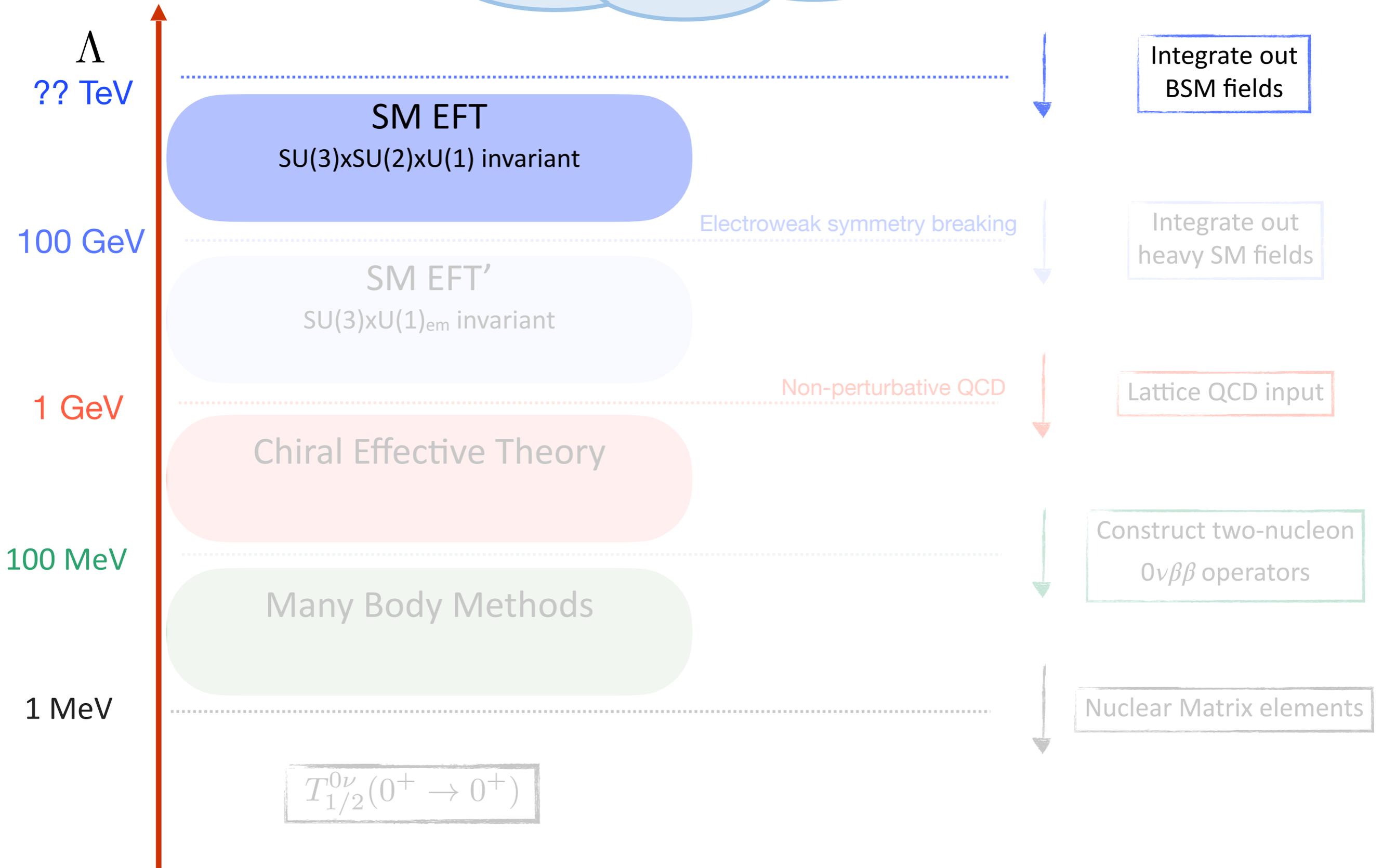
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- However, if  $c_5 = \mathcal{O}(1)$ ,  $\Lambda = 10^{15}\text{ GeV}$  dimension-7, -9 irrelevant in this case

# Outline

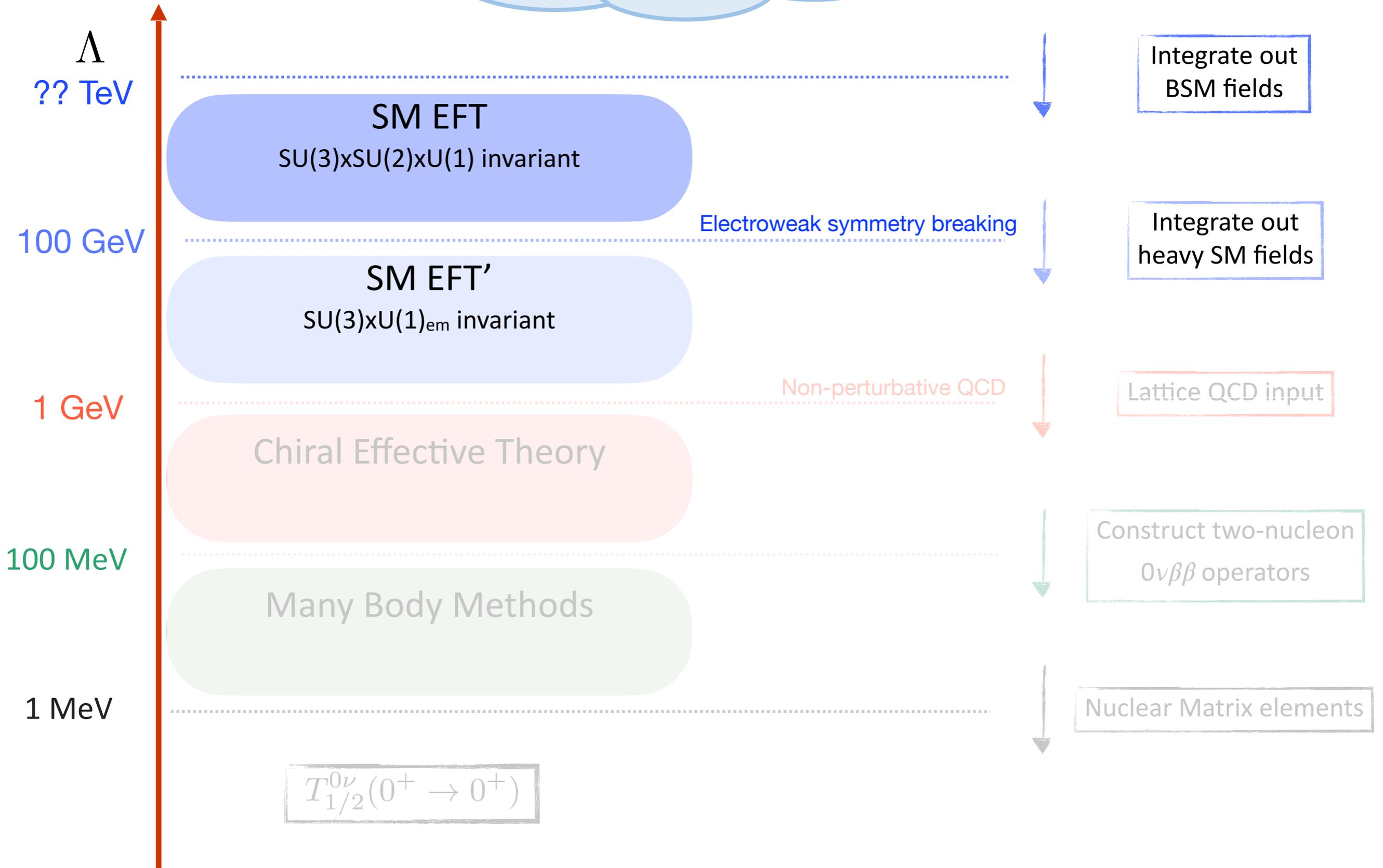
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$$T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)$$

# Outline

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# Running/matching at the weak scale

SM EFT

SU(3)xSU(2)xU(1) invariant

$$\mathcal{L} = \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)} + \frac{c_i^{(9)}}{\Lambda^5} O_i^{(9)}$$

Electroweak symmetry breaking

SM EFT'

SU(3)xU(1) invariant

$$\mathcal{L} = \frac{c_i^{(3)}}{\Lambda} O_i^{(3)} + \frac{c_i^{(6)}}{\Lambda^3} O_i^{(6)} + \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)} + \frac{c_i^{(9)}}{\Lambda^5} O_i^{(9)}$$

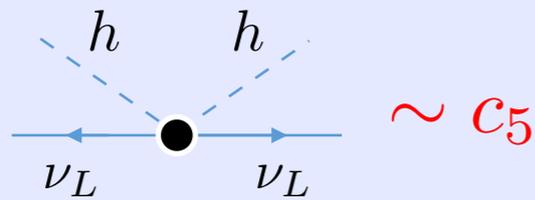
$M_{EW}$   
100 GeV

- Mismatch in dimensions due to insertions of the Higgs vacuum expectation value

# Low-energy operators

## Summary

SU(3)xSU(2)xU(1) invariant EFT



$M_{EW}$   
100 GeV

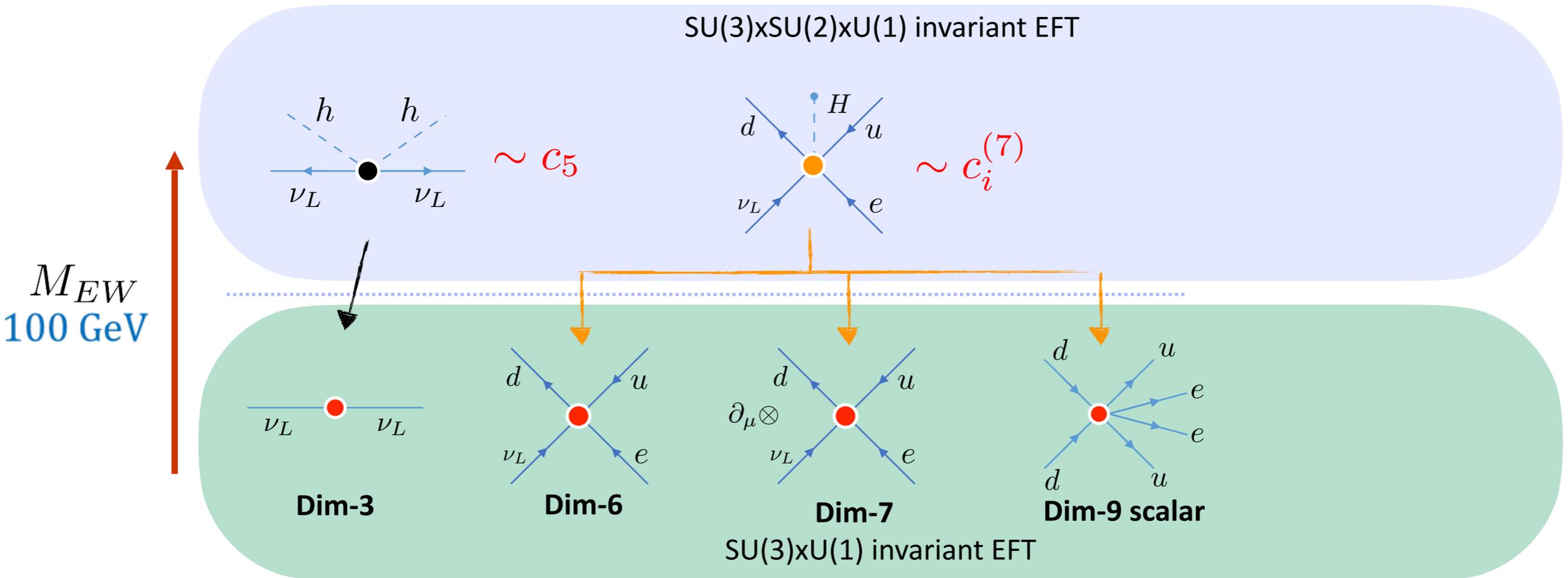


Dim-3

SU(3)xU(1) invariant EFT

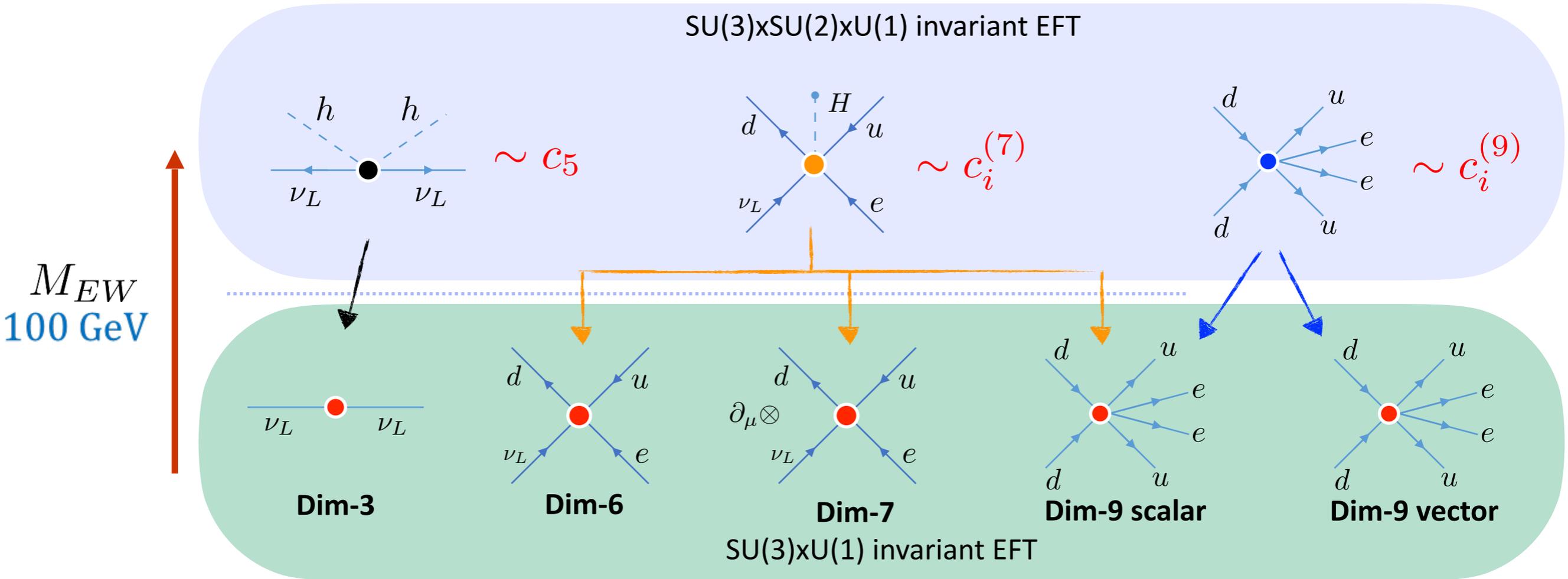
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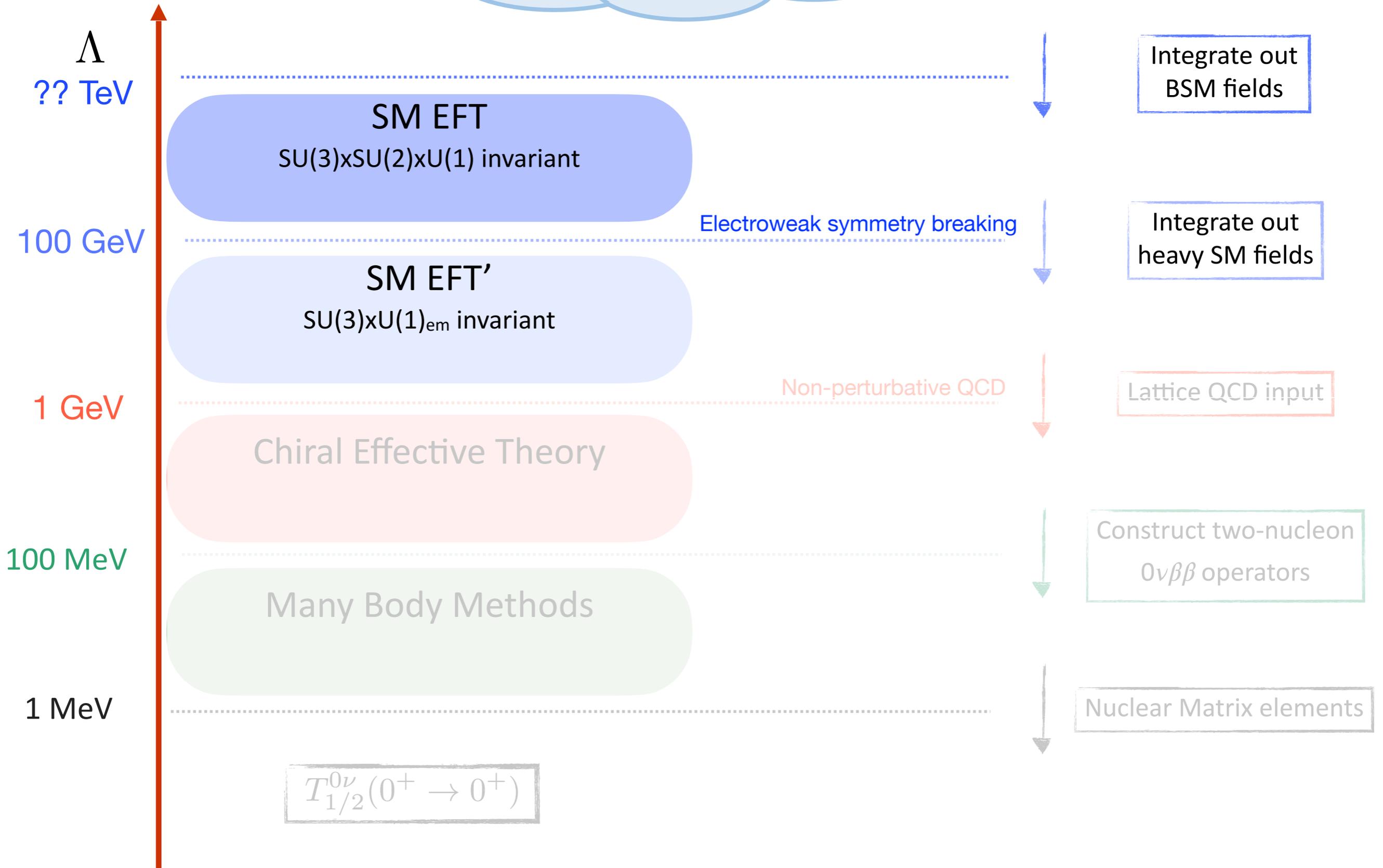
# Low-energy operators

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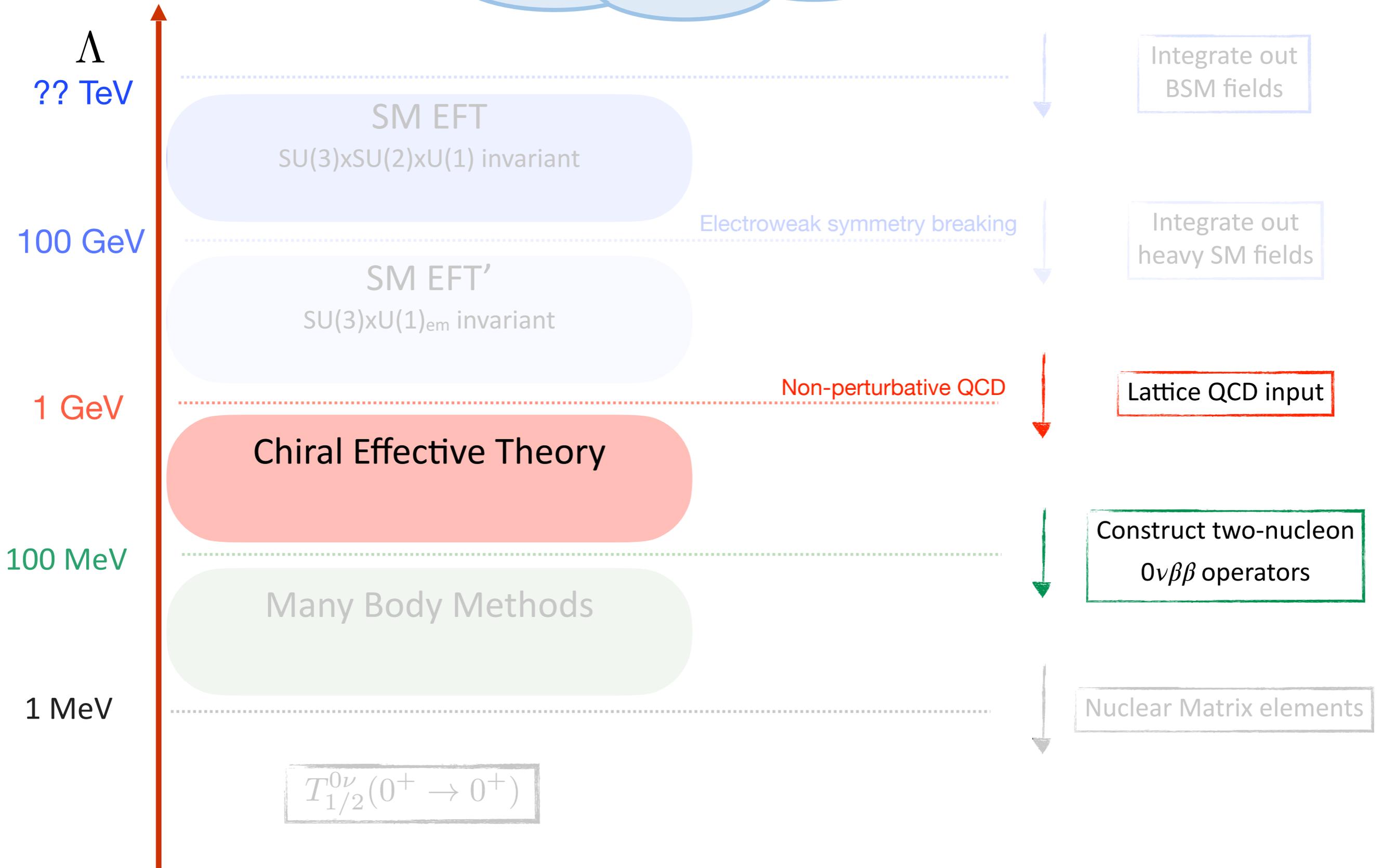
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Lepton-number violation:  
seesaw, left-right model, leptoquarks,...

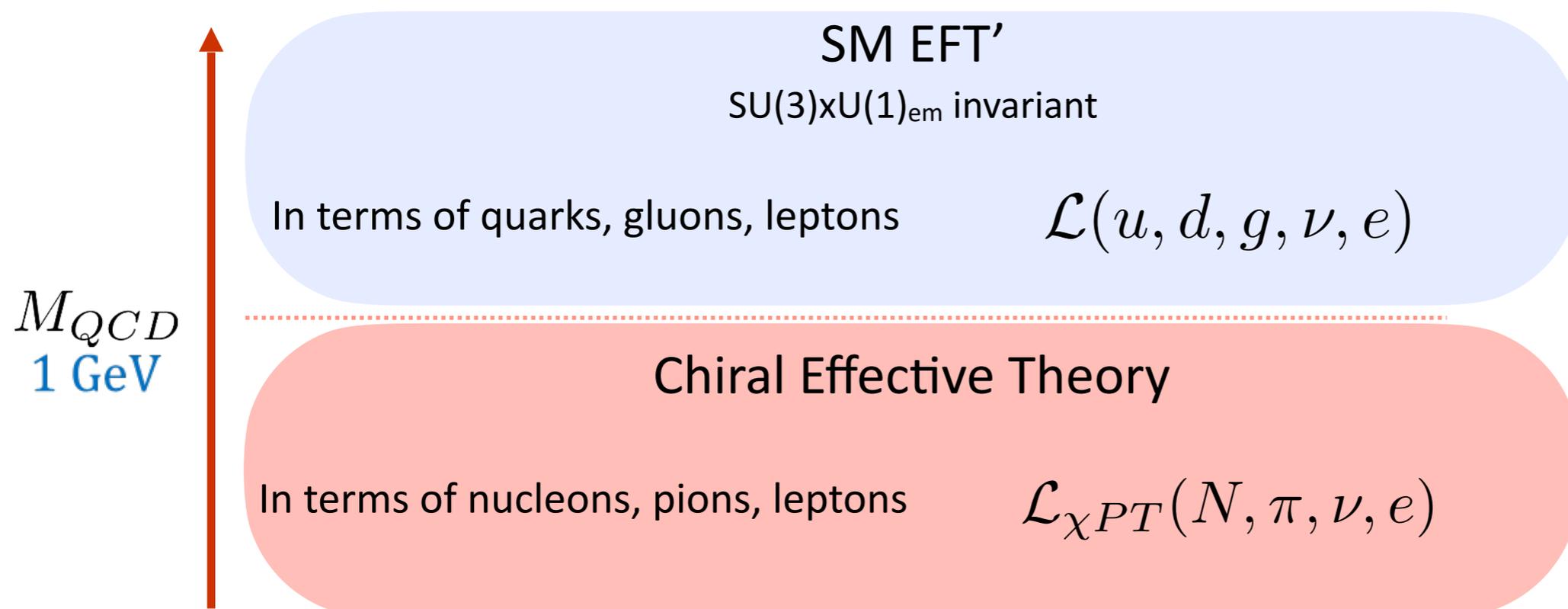


# Outline

Lepton-number violation:  
seesaw, left-right model, leptoquarks,...



# Matching to Chiral EFT



Form of operators determined by chiral symmetry

The operators come with unknown constants (LECs)

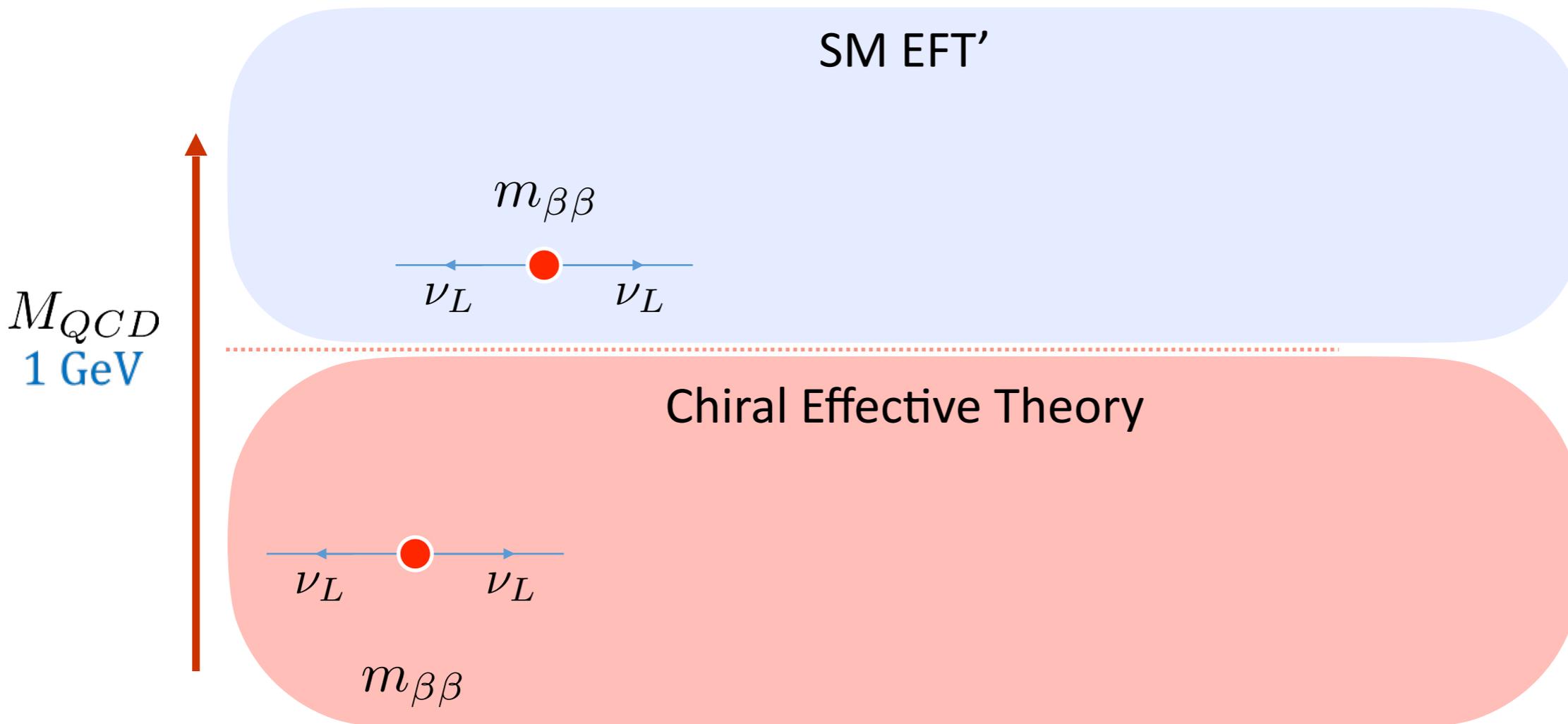
Need a power-counting scheme

- Start by assuming Naive dimensional analysis (NDA)
- Will come back to whether it breaks down

# Matching to Chiral EFT

Dimension-3

Warning: Based on NDA

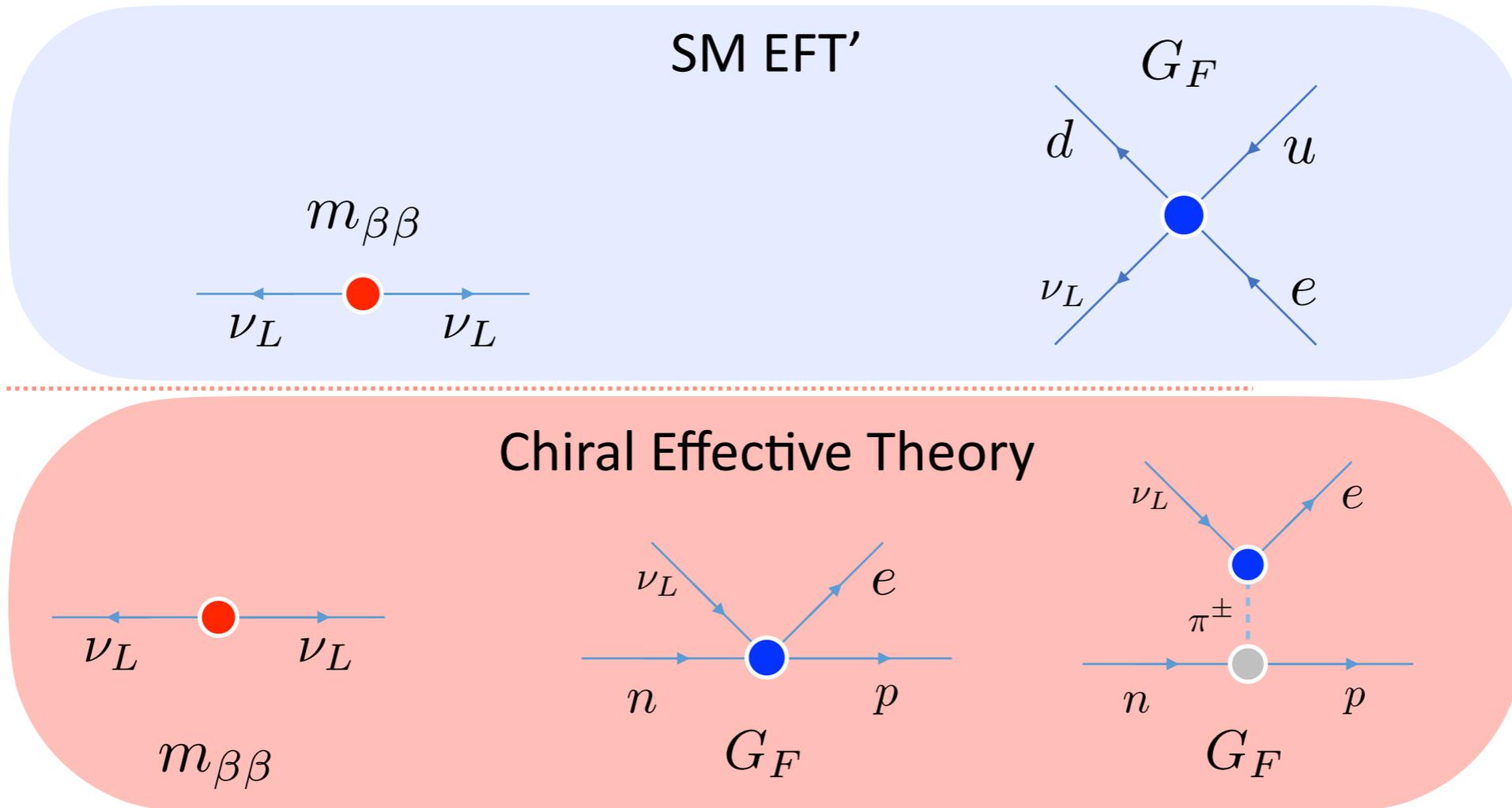


# Matching to Chiral EFT

Dimension-3

Warning: Based on NDA

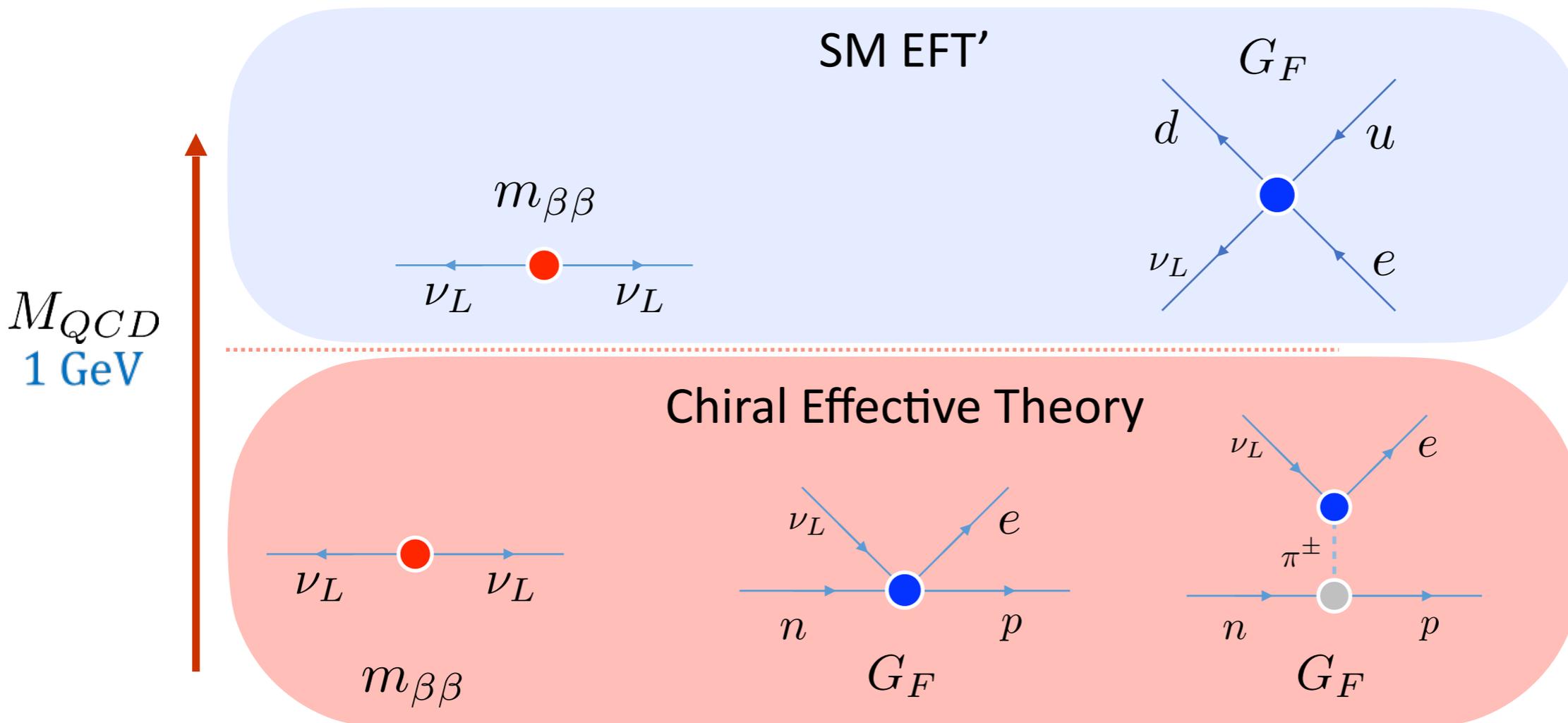
$M_{QCD}$   
1 GeV



# Matching to Chiral EFT

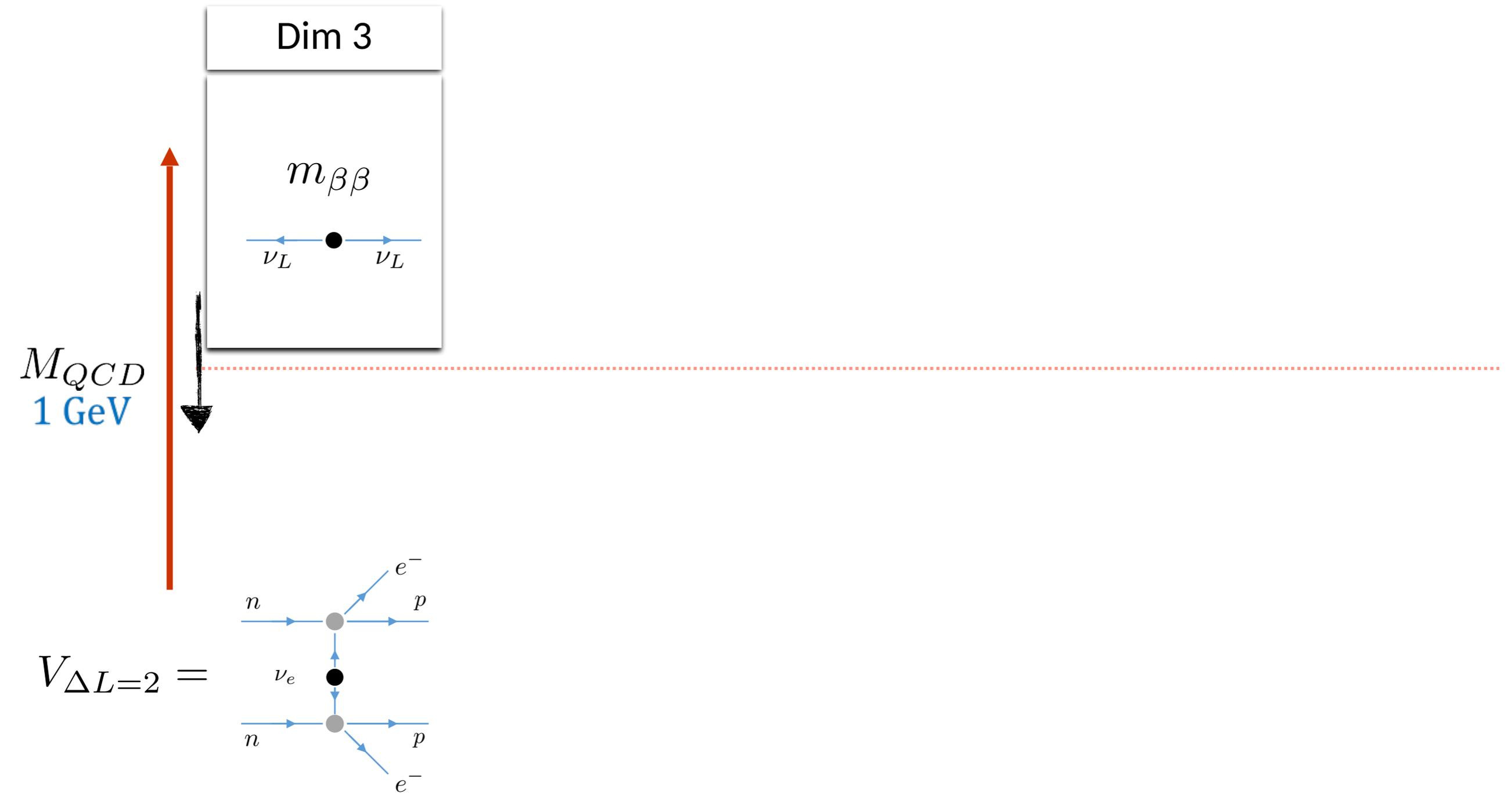
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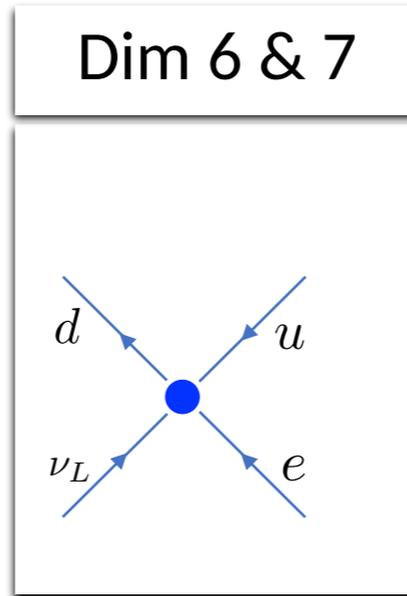
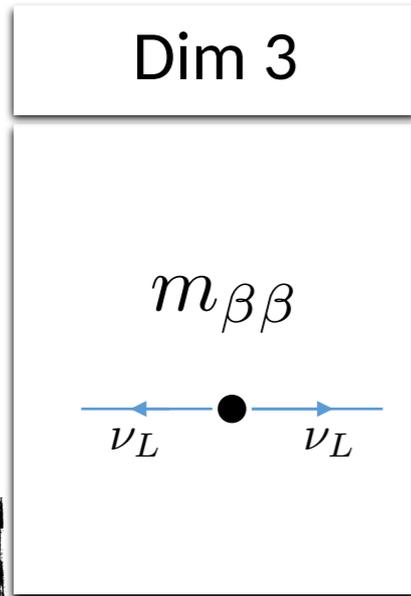


- At LO in Weinberg counting, only need the nucleon one-body currents
  - The needed low-energy constants are the nucleon charges  $g_V, g_A$
  - Known from experiment / Lattice QCD

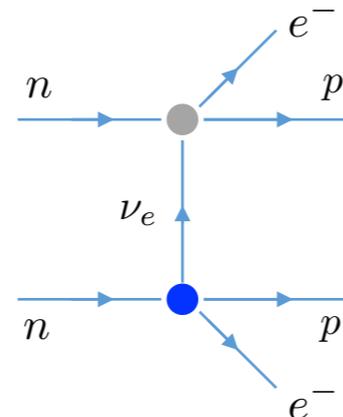
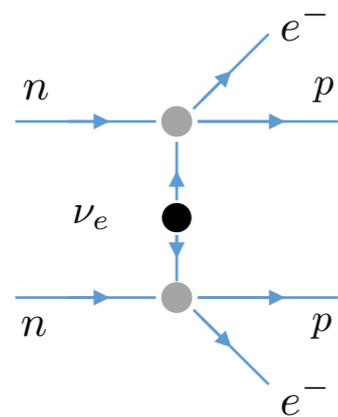
# Chiral EFT



# Chiral EFT



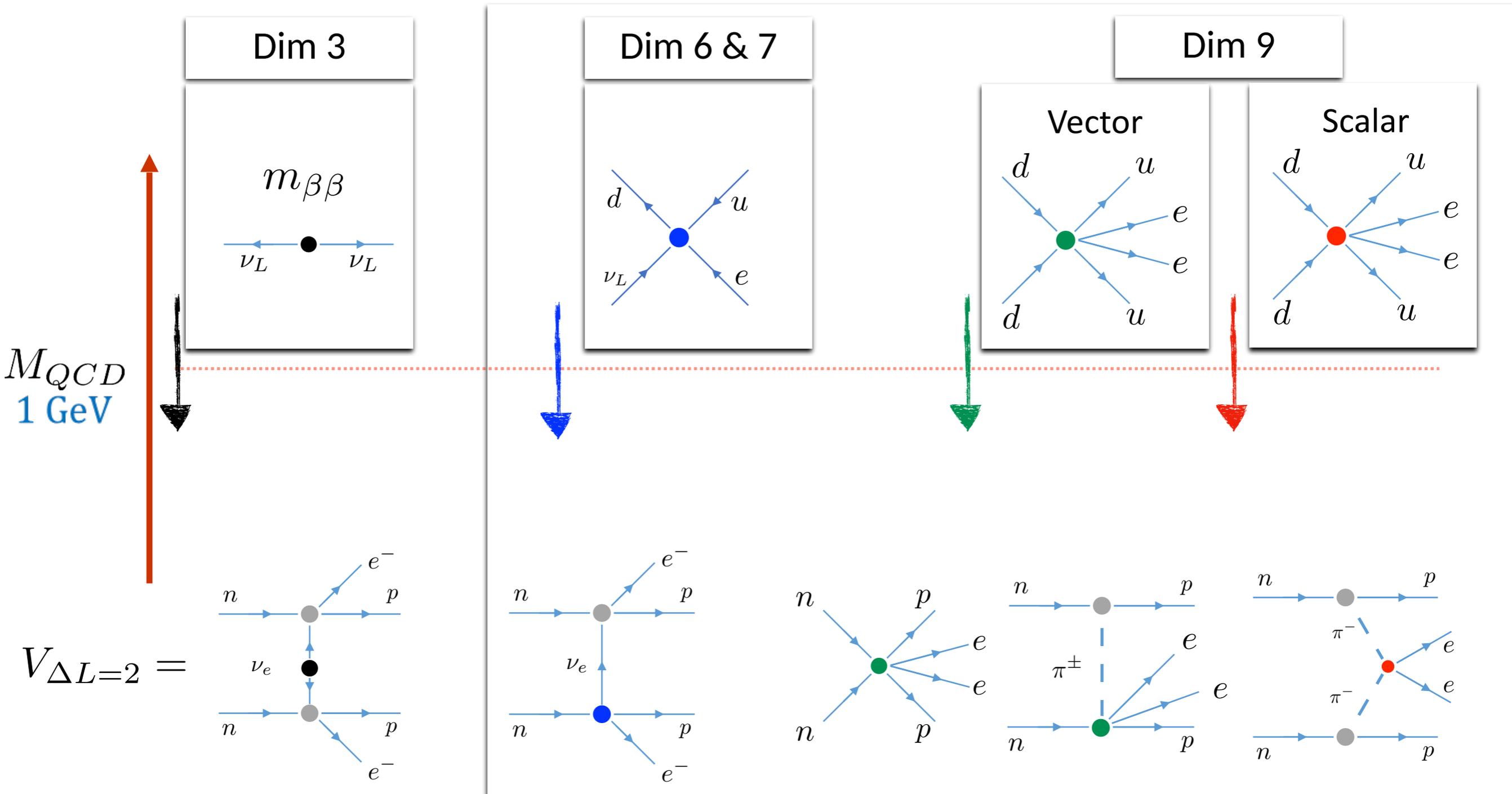
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Matching similar for higher-dimensional operators:

- Additional  $\pi\pi$ ,  $\pi N$ ,  $NN$  interactions
- New Low-energy constants

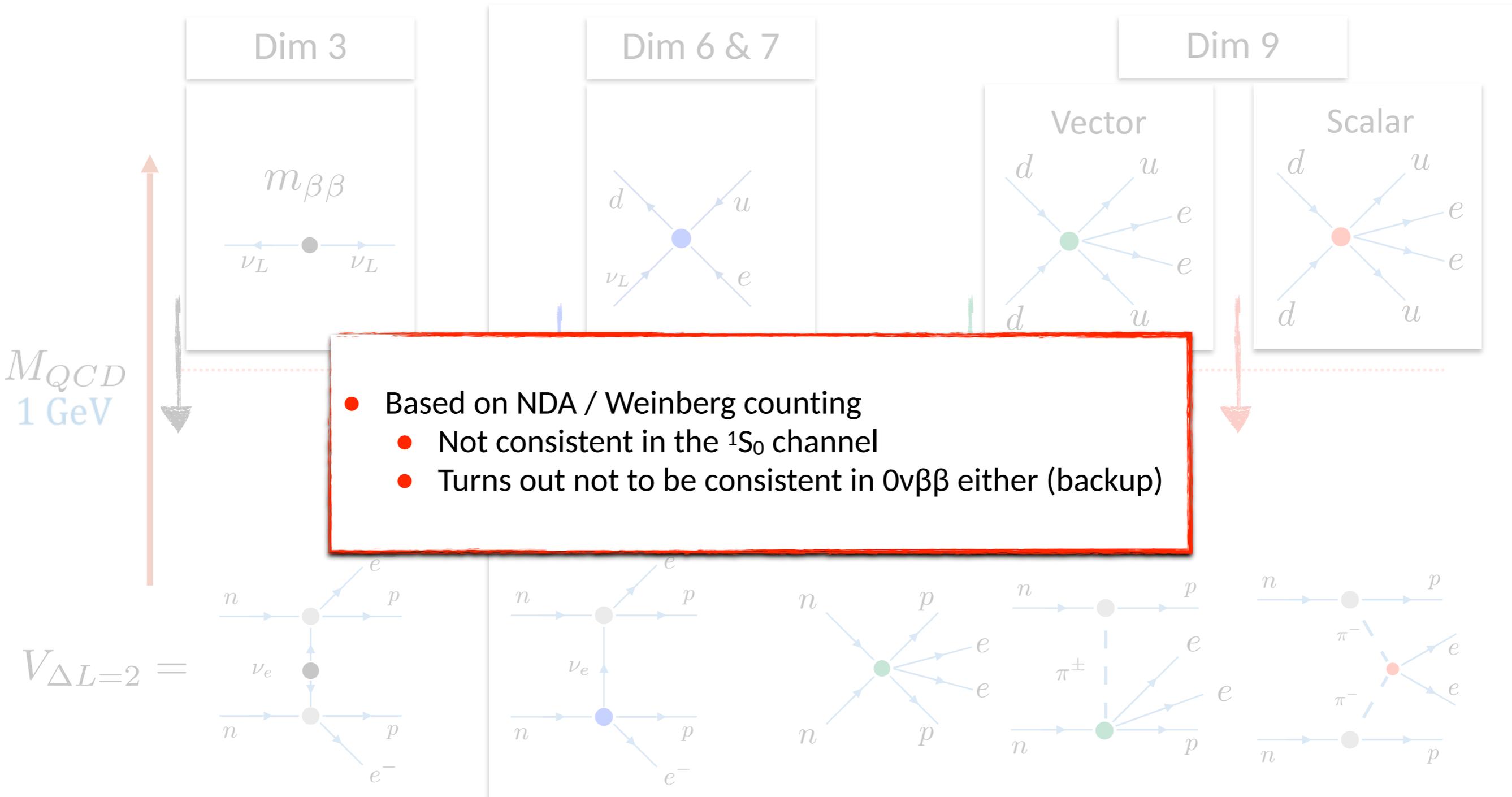
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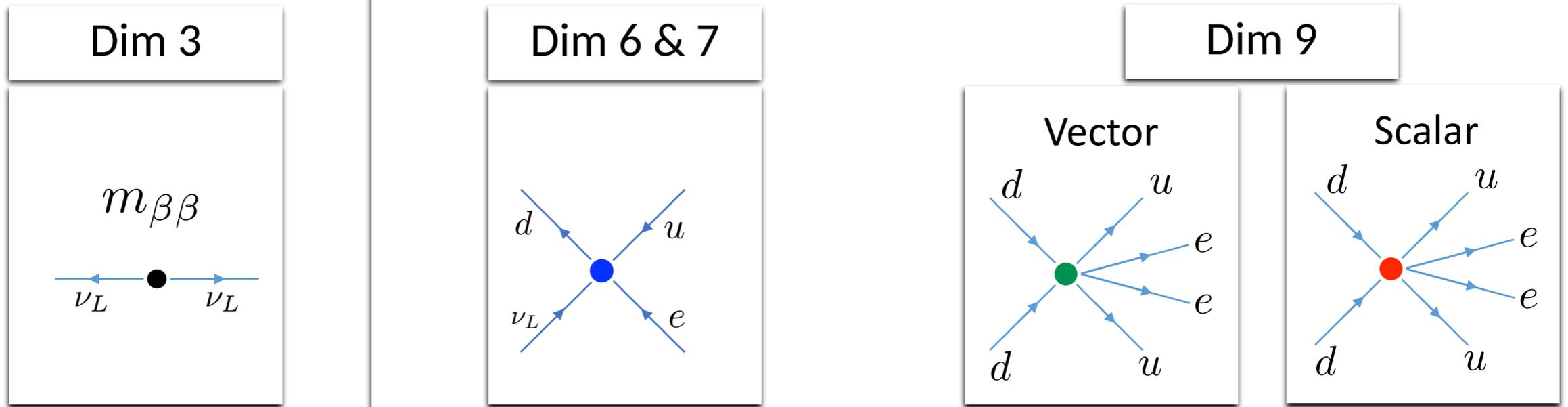


- Based on NDA / Weinberg counting
  - Not consistent in the  $^1S_0$  channel
  - Turns out not to be consistent in  $0\nu\beta\beta$  either (backup)

Matching similar for higher-dimensional operators:

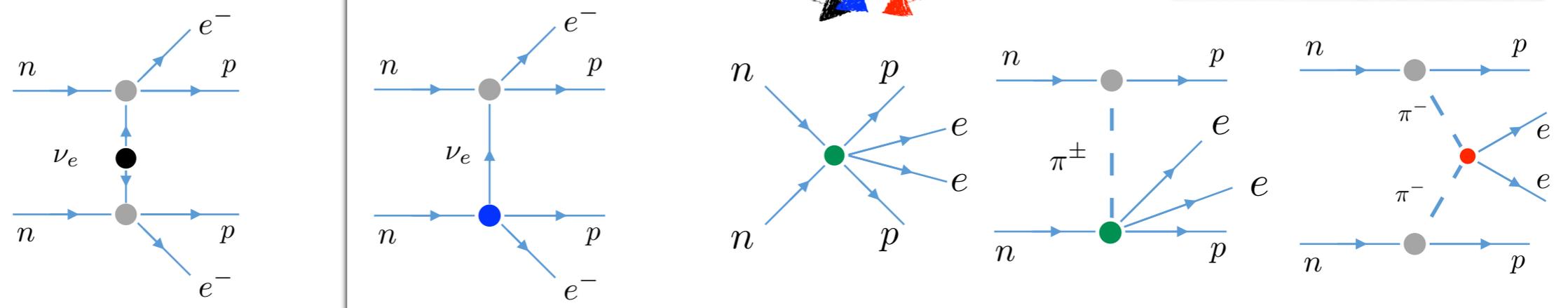
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# Chiral EFT



$M_{QCD}$   
1 GeV

$V_{\Delta L=2} =$



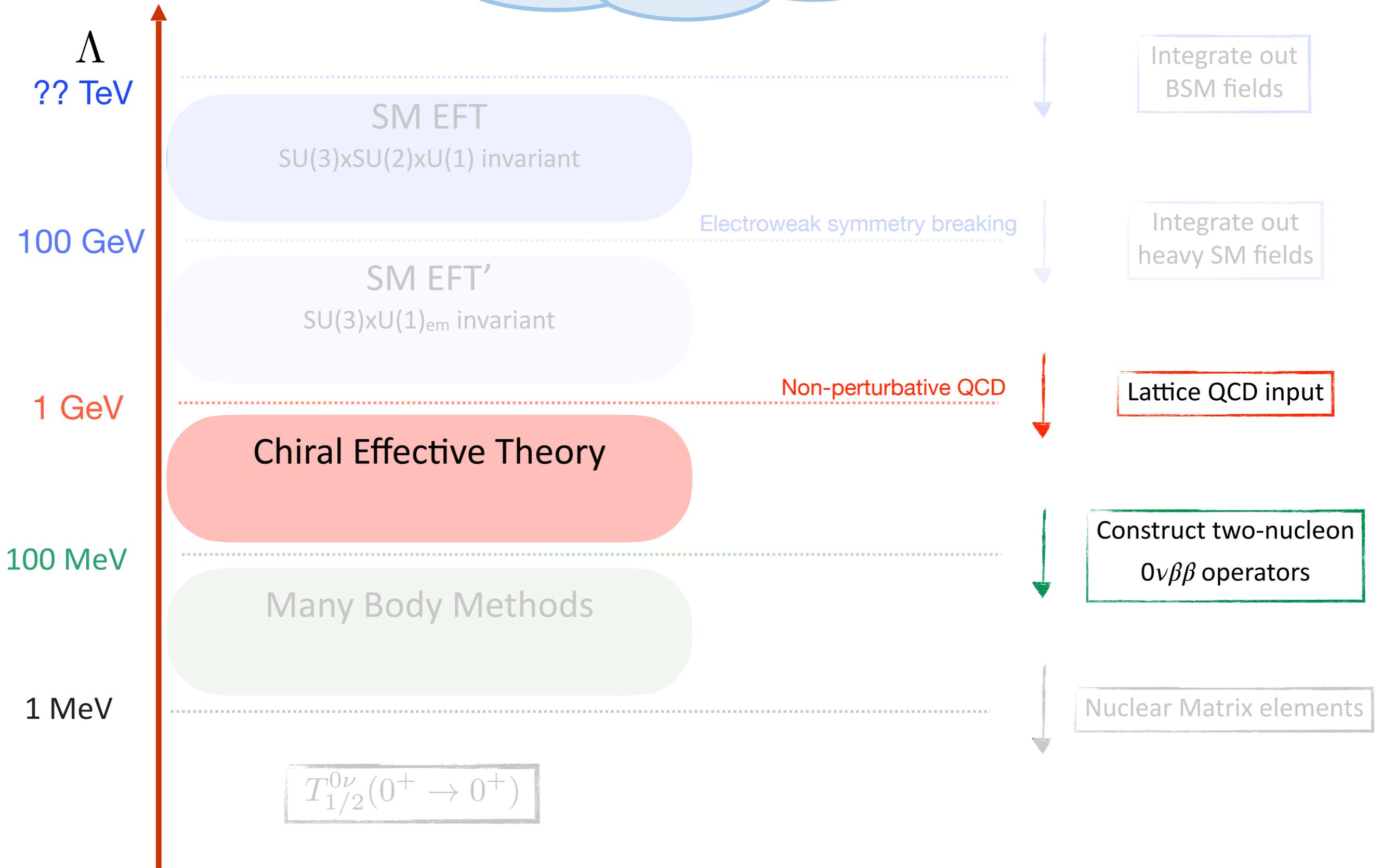
1+2+4 'non-NDA' contact interactions

Matching similar for higher-dimensional operators:

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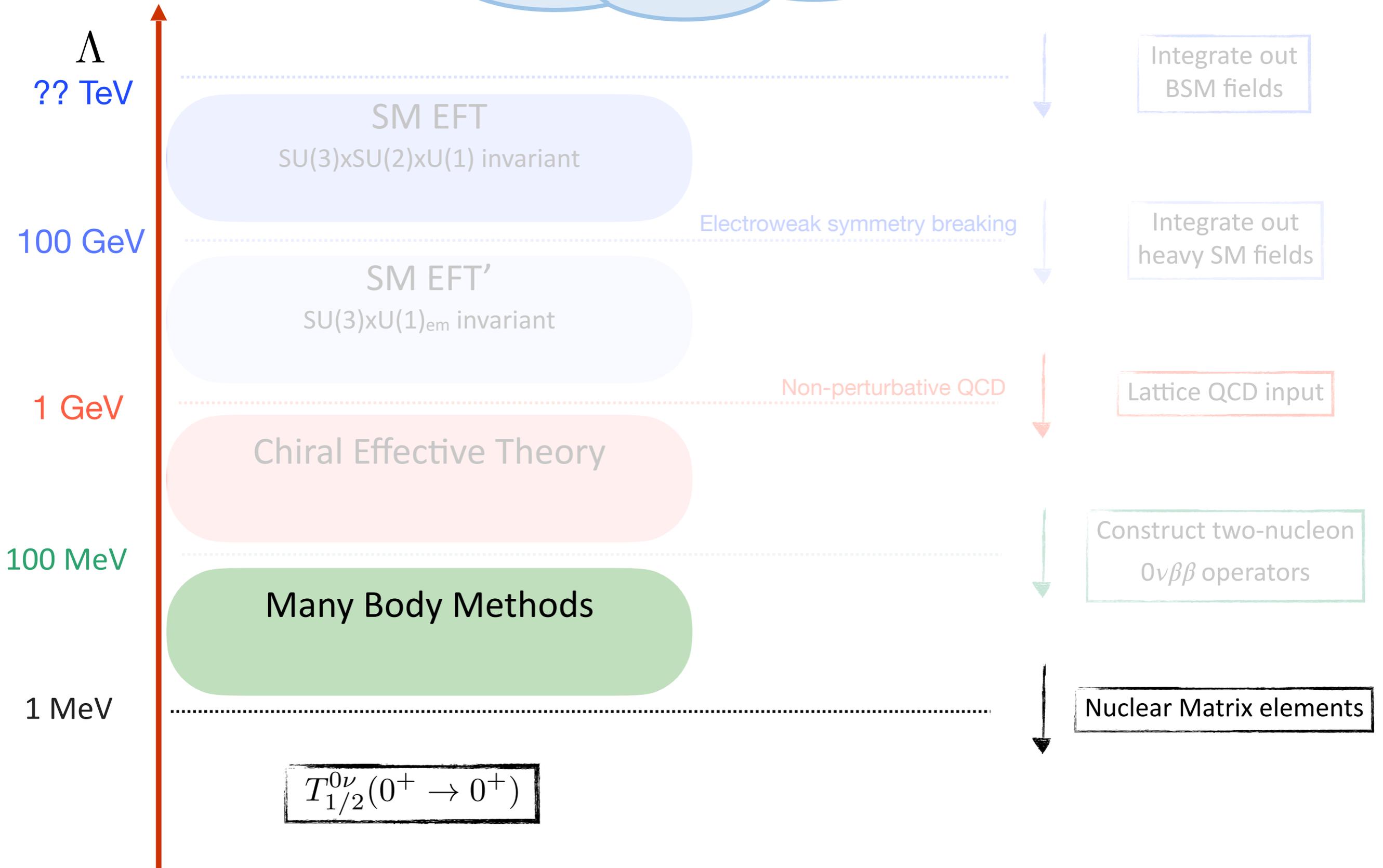
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Lepton-number violation:  
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# The $0\nu\beta\beta$ half-life

$$\Gamma^{0\nu}(0^+ \rightarrow 0^+) \sim \left| \langle 0^+ | \sum_{\text{nucleons}} \int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{i\mathbf{q}\cdot\mathbf{r}} V(\mathbf{q}^2) | 0^+ \rangle \right|^2 = \sum_{i,j} G_{i,j} M_i M_j g_i g_j C_i C_j^*$$

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# Nuclear matrix elements

- All NMEs can be obtained from those of light/heavy neutrino exchange
  - 9 long-distance & 6 short-distance
  - Have been determined in literature

- Follow ChiPT expectations fairly well
  - E.g. all  $O(1)$  and

$$M_{GT, sd}^{PP} = -\frac{1}{2}M_{GT, sd}^{AP} - M_{GT}^{PP}, \quad M_{T, sd}^{PP} = -\frac{1}{2}M_{T, sd}^{AP} - M_T^{PP},$$

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NMEs	$^{76}\text{Ge}$			
	[74]	[31]	[81]	[82, 83]
$M_F$	-1.74	-0.67	-0.59	-0.68
$M_{GT}^{AA}$	5.48	3.50	3.15	5.06
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NMEs	$^{76}\text{Ge}$			
	$M_{F, sd}$	-3.46	-1.55	-1.46
$M_{GT, sd}^{AA}$	11.1	4.03	4.87	3.62
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$M_{GT, sd}^{PP}$	1.99	0.85	0.82	0.42
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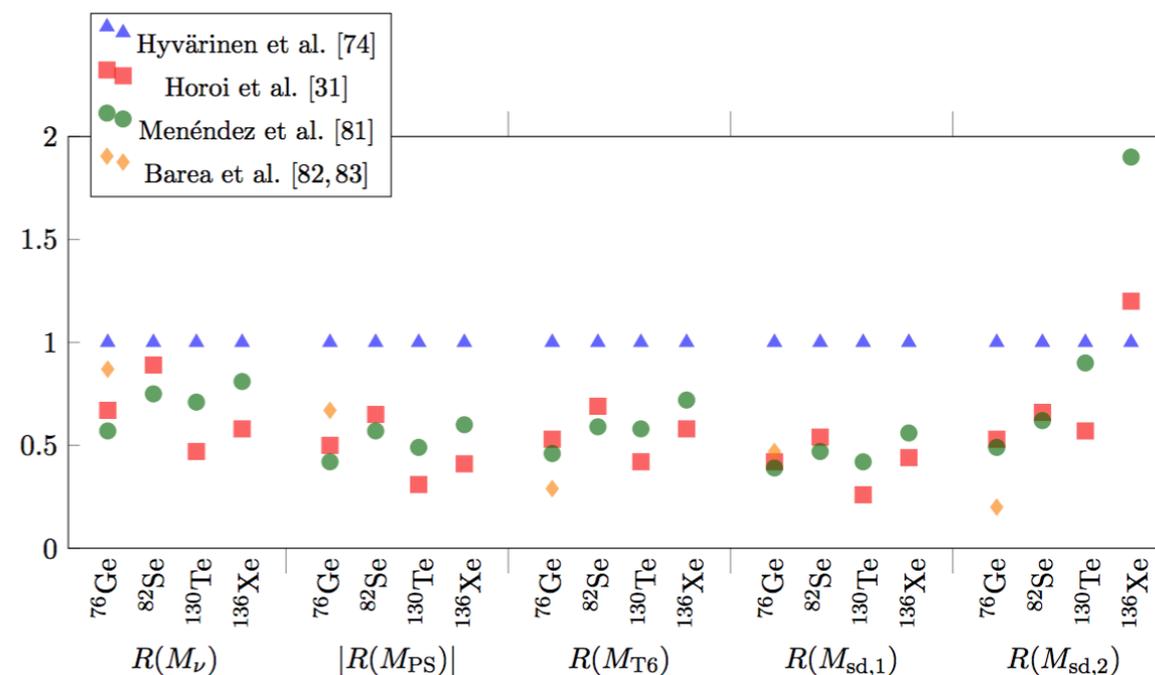
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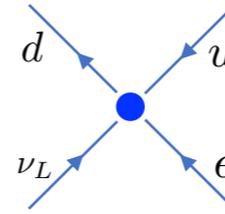
- The NMEs differ by a factor 2-3 between methods
  - For Majorana-mass term & other LNV sources



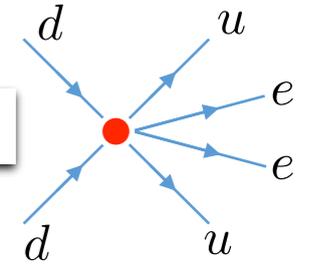
# Phenomenology

# Current limits

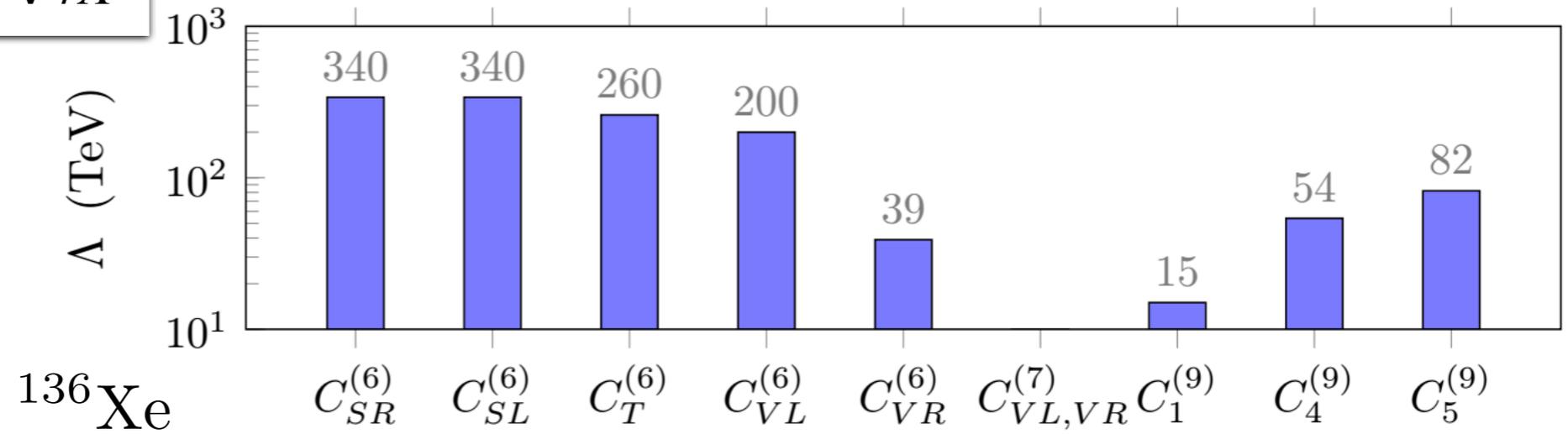
Dim 6 & 7



Dim 9



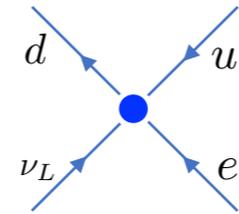
- Couplings with  $C_i \sim v^3/\Lambda^3$



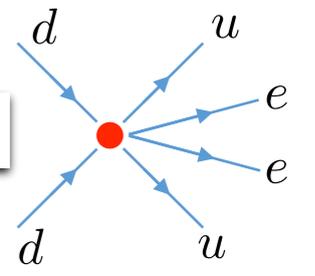
$^{136}\text{Xe}$

# Current limits

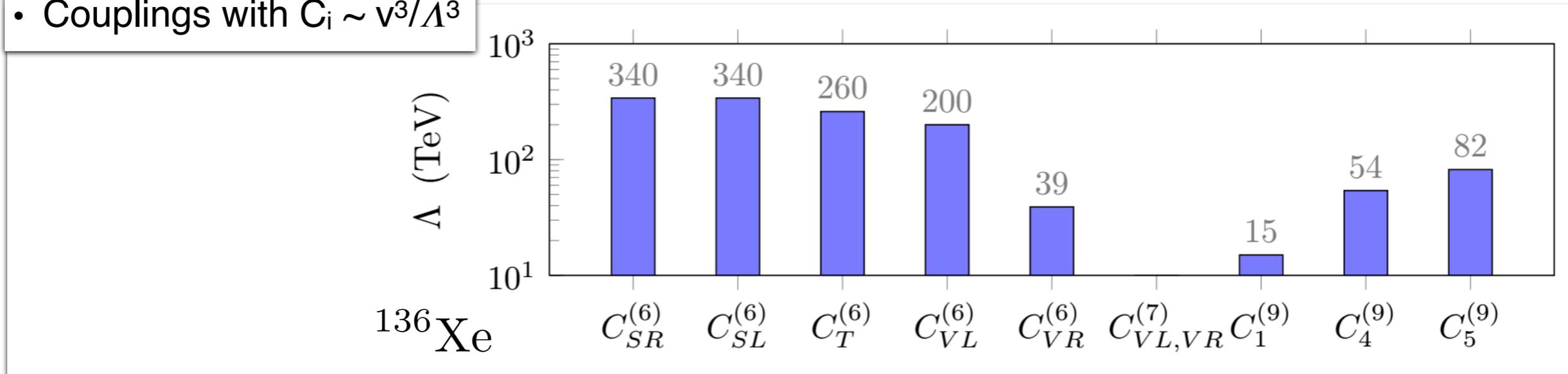
Dim 6 & 7



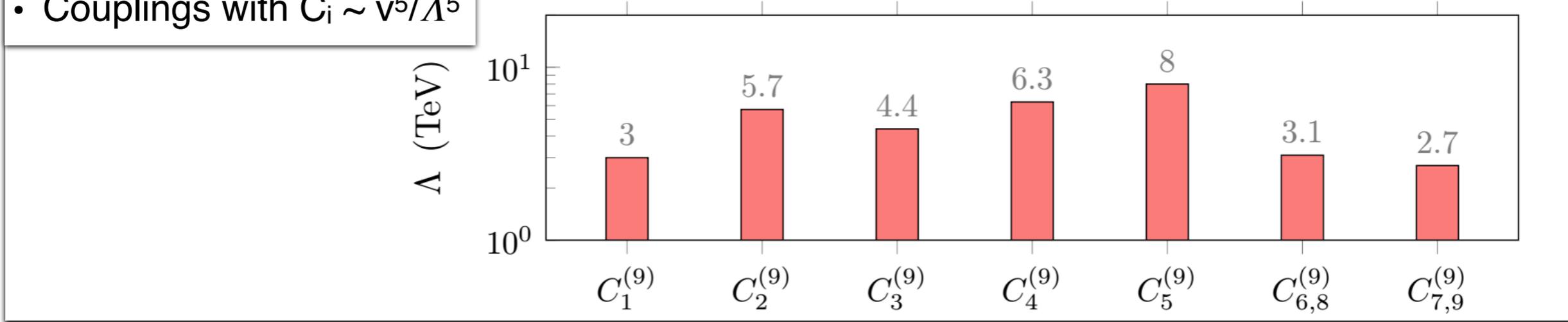
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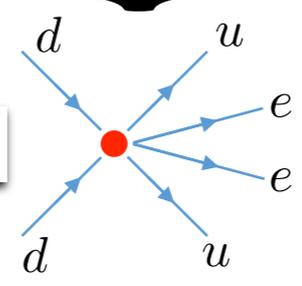
• Couplings with  $C_i \sim v^3/\Lambda^3$



• Couplings with  $C_i \sim v^5/\Lambda^5$

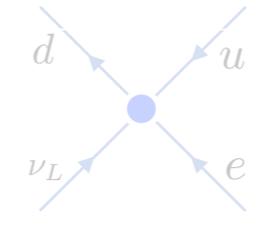


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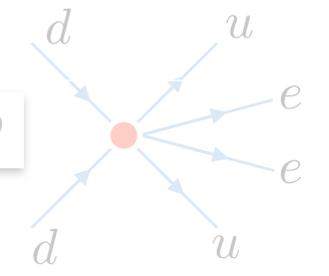


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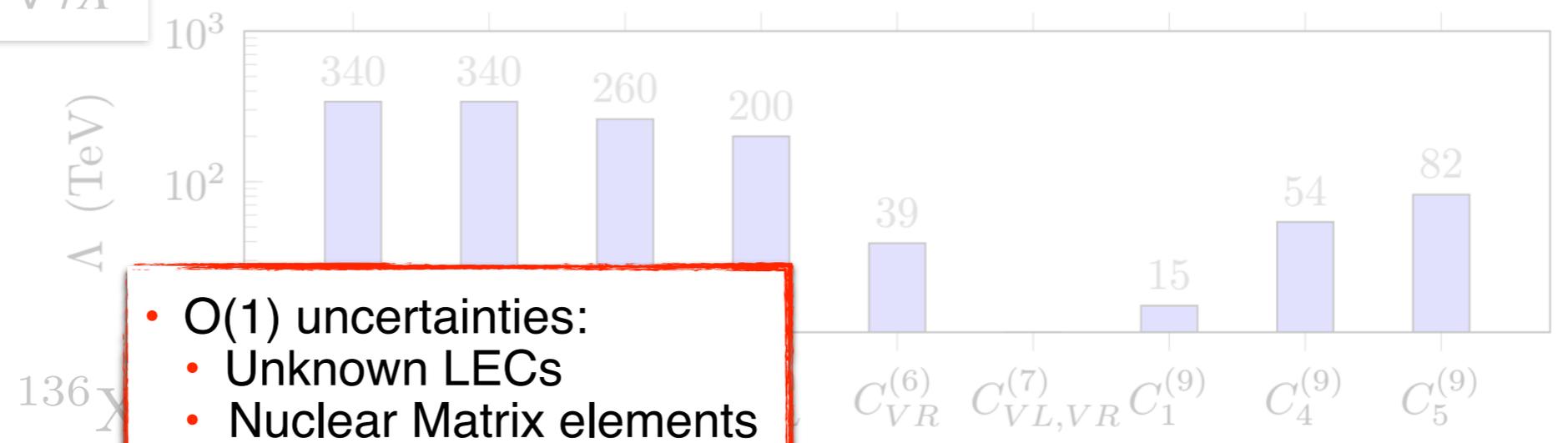
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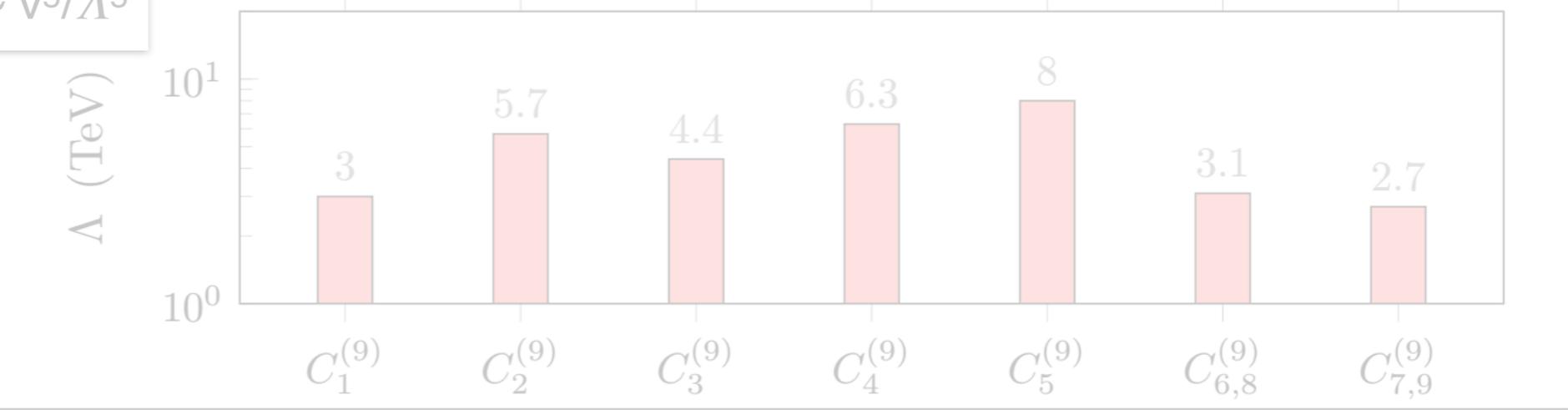
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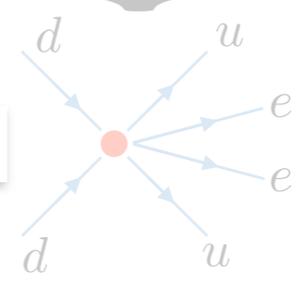
Couplings with  $C_i \sim v^3/\Lambda^3$



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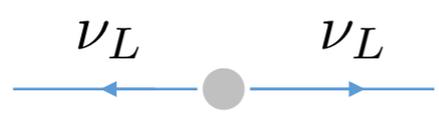
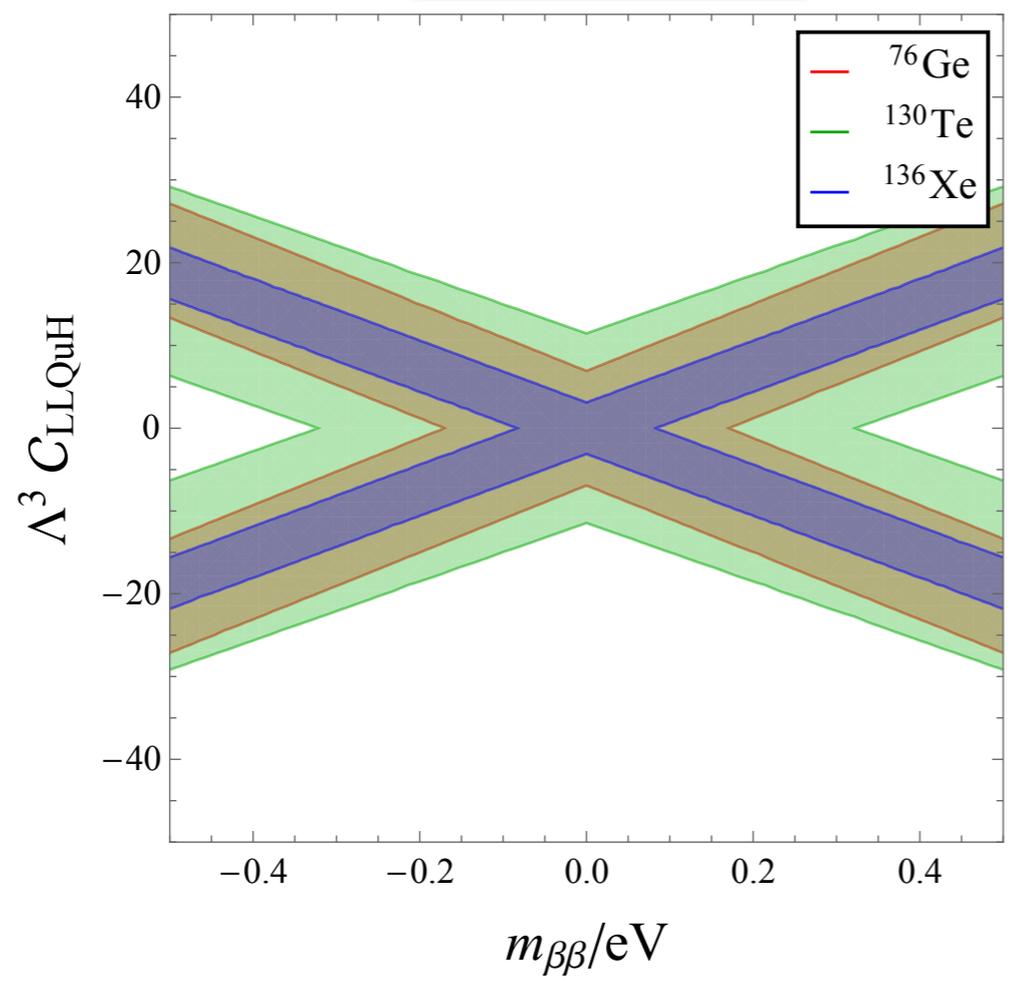
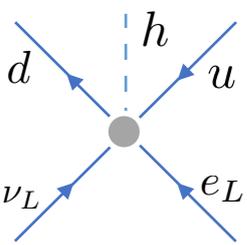
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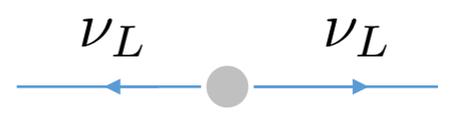
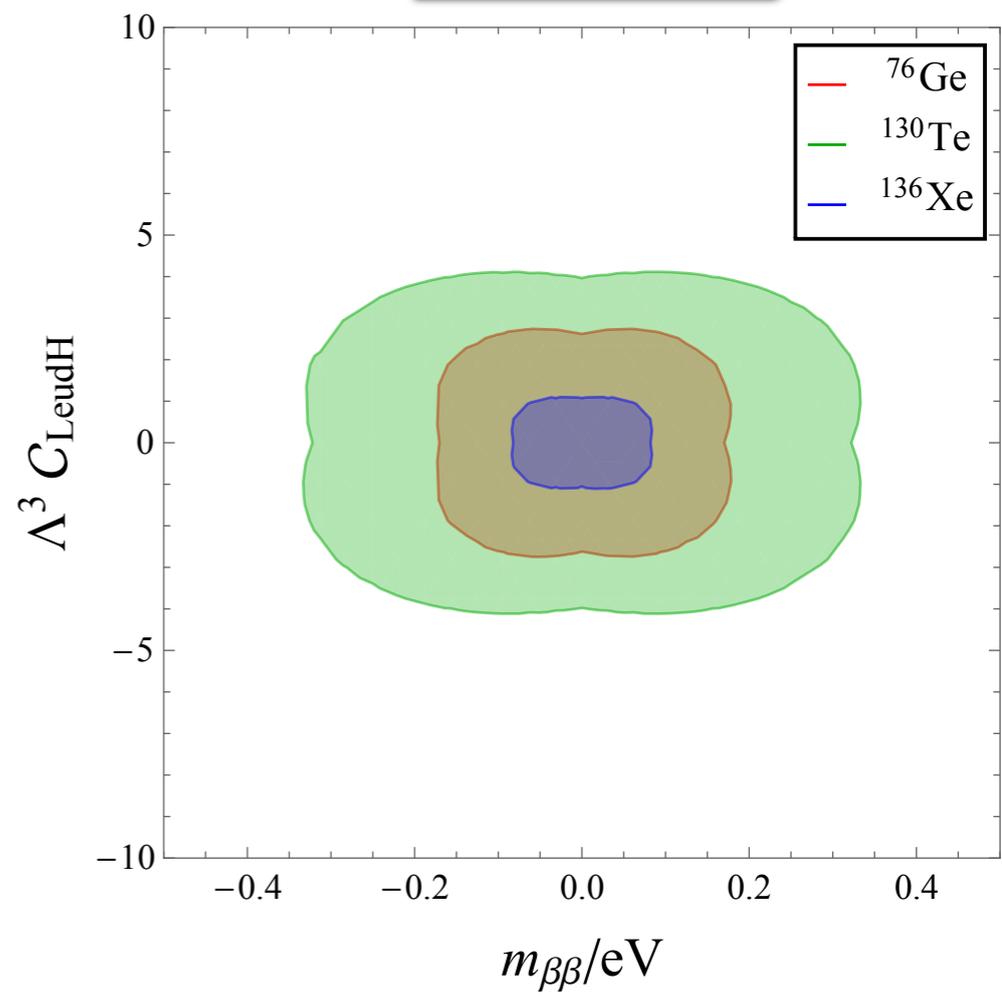
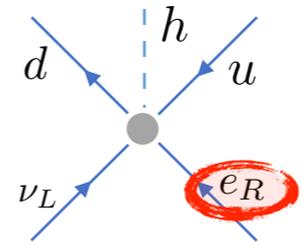
# Current limits

## Two-coupling analysis

$\Lambda=600$  TeV



$\Lambda=40$  TeV



# Disentangling operators

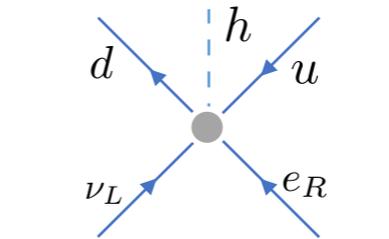
# Disentangling operators

What if a  $0\nu\beta\beta$  signal is measured?

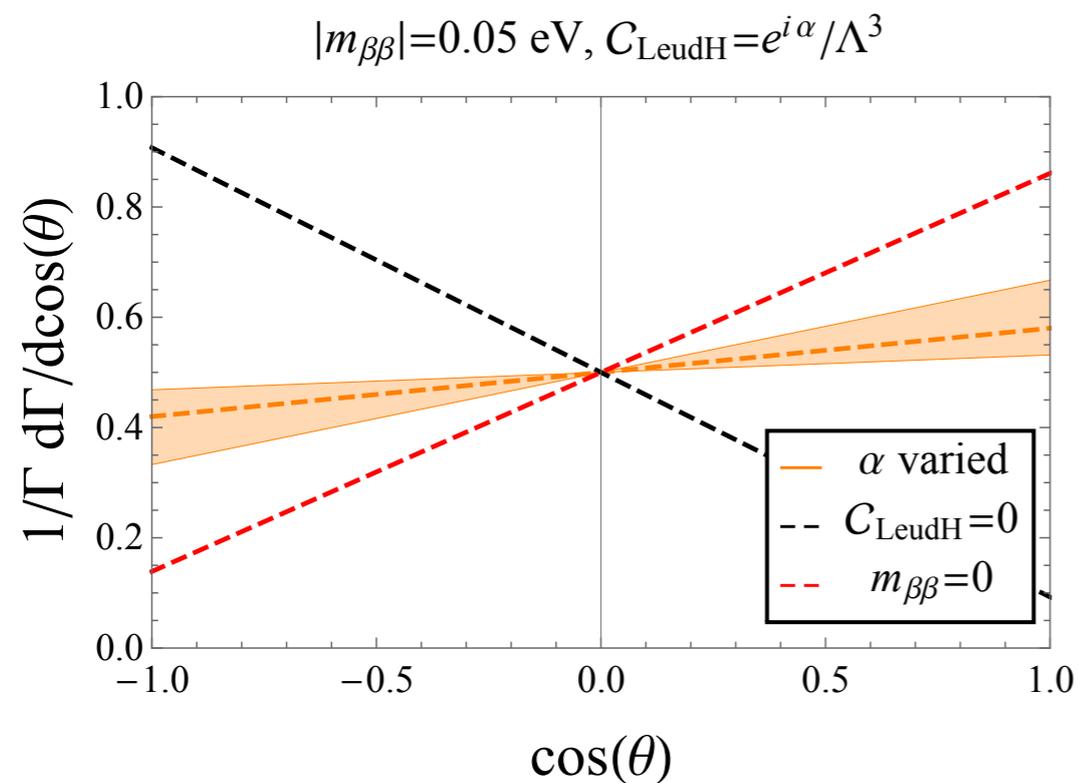
- Picking the allowed values



$$m_{\beta\beta} = 0.05 \text{ eV}$$



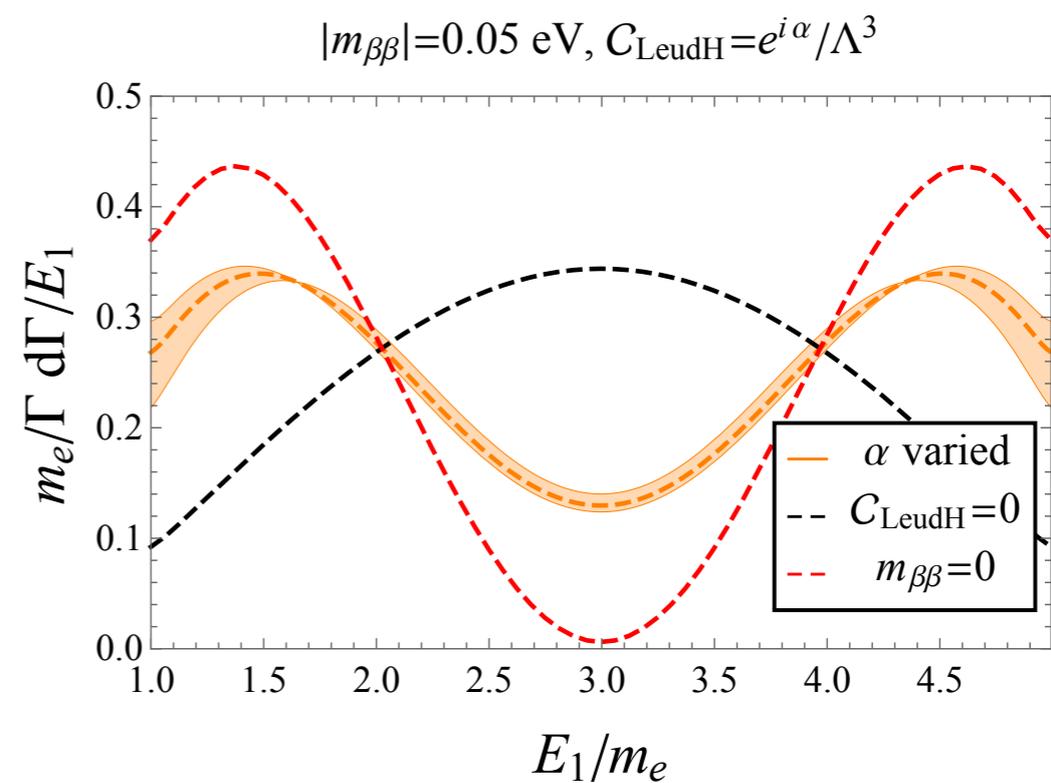
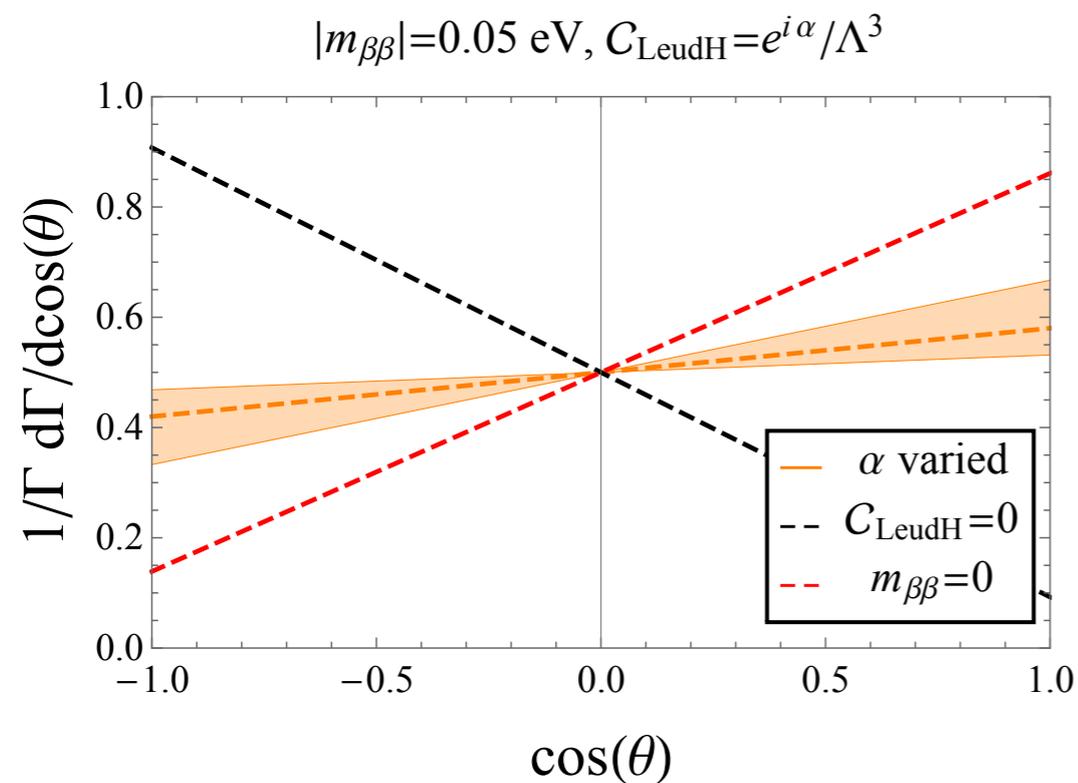
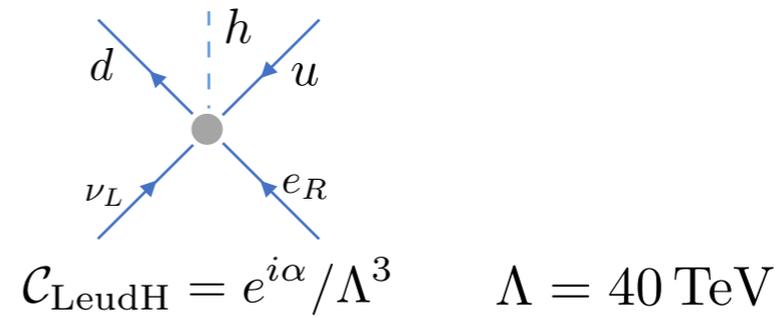
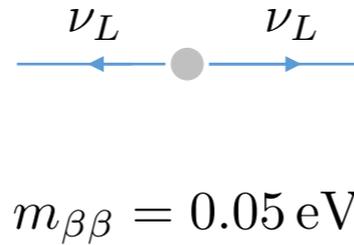
$$C_{\text{LeudH}} = e^{i\alpha} / \Lambda^3 \quad \Lambda = 40 \text{ TeV}$$



# Disentangling operators

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# Light (almost) sterile neutrinos

Based on arXiv:2002.07182

G. Zhou, K. Fuyuto, J. de Vries, E. Mereghetti, WD

# Sterile neutrinos

- Could play a role in leptogenesis [Canetti et al. '13](#)
- Provides a dark matter candidate [Boyarski et al. '19](#)
- Appear in Left-Right models / Leptoquark scenarios / Grand Unified Theories
- Have been suggested as a solution to neutrino oscillation experiments [Böser et al. '19](#)

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- Add sterile effects by including:

$$\mathcal{L}_{\nu_R} = i\bar{\nu}_R \not{\partial} \nu_R - \frac{1}{2} \bar{\nu}_R^c M_R \nu_R - \bar{L} \tilde{H} Y_D \nu_R + \mathcal{L}_{\nu_R}^{(6)} + \mathcal{L}_{\nu_R}^{(7)}$$

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- Majorana mass  
(L violating)

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- Dirac mass  
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Liao & Ma, '17

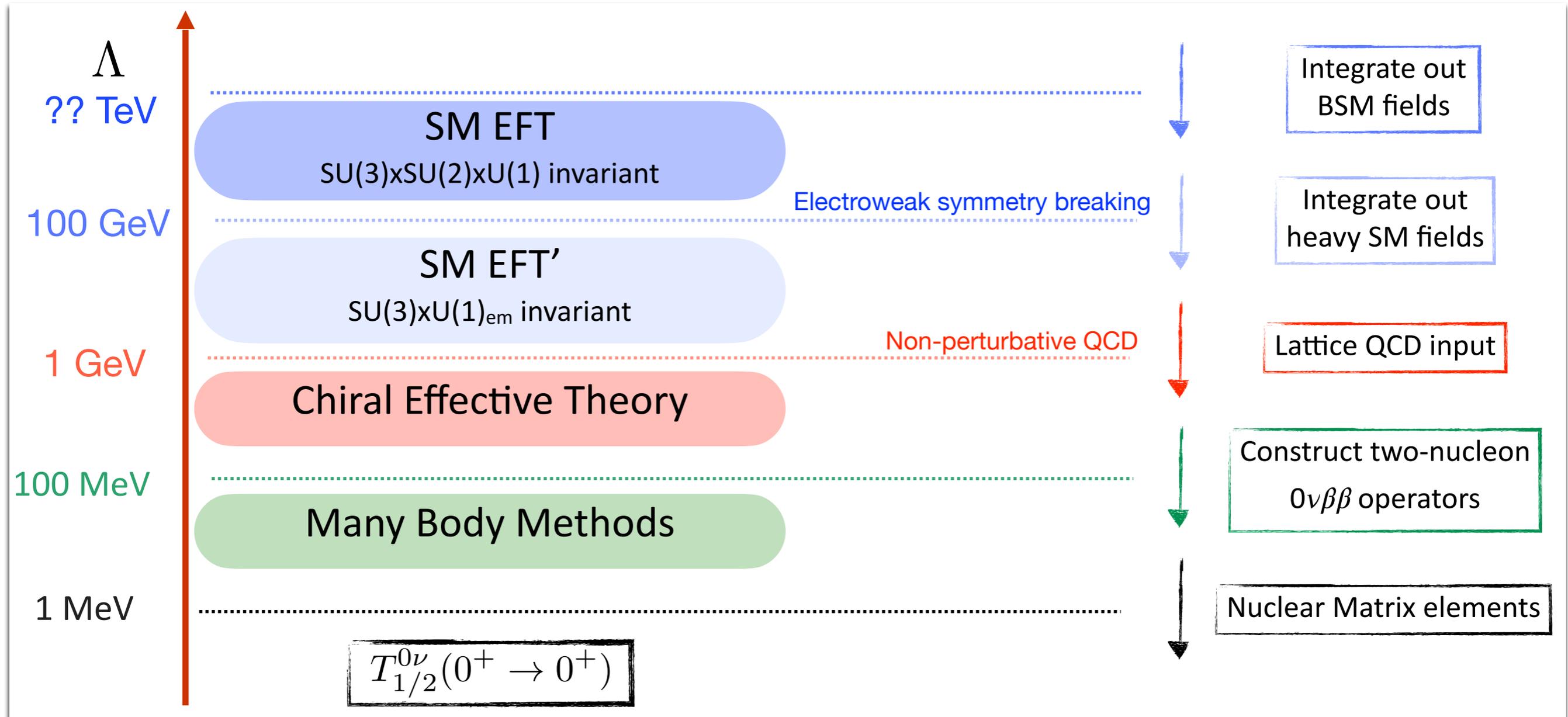
- Majorana mass  
(L violating)

- Dirac mass  
(L conserving)

- Dimension-6 (L-conserving)
- Dimension-7 operators (L-violating)
- Induced by heavy BSM physics

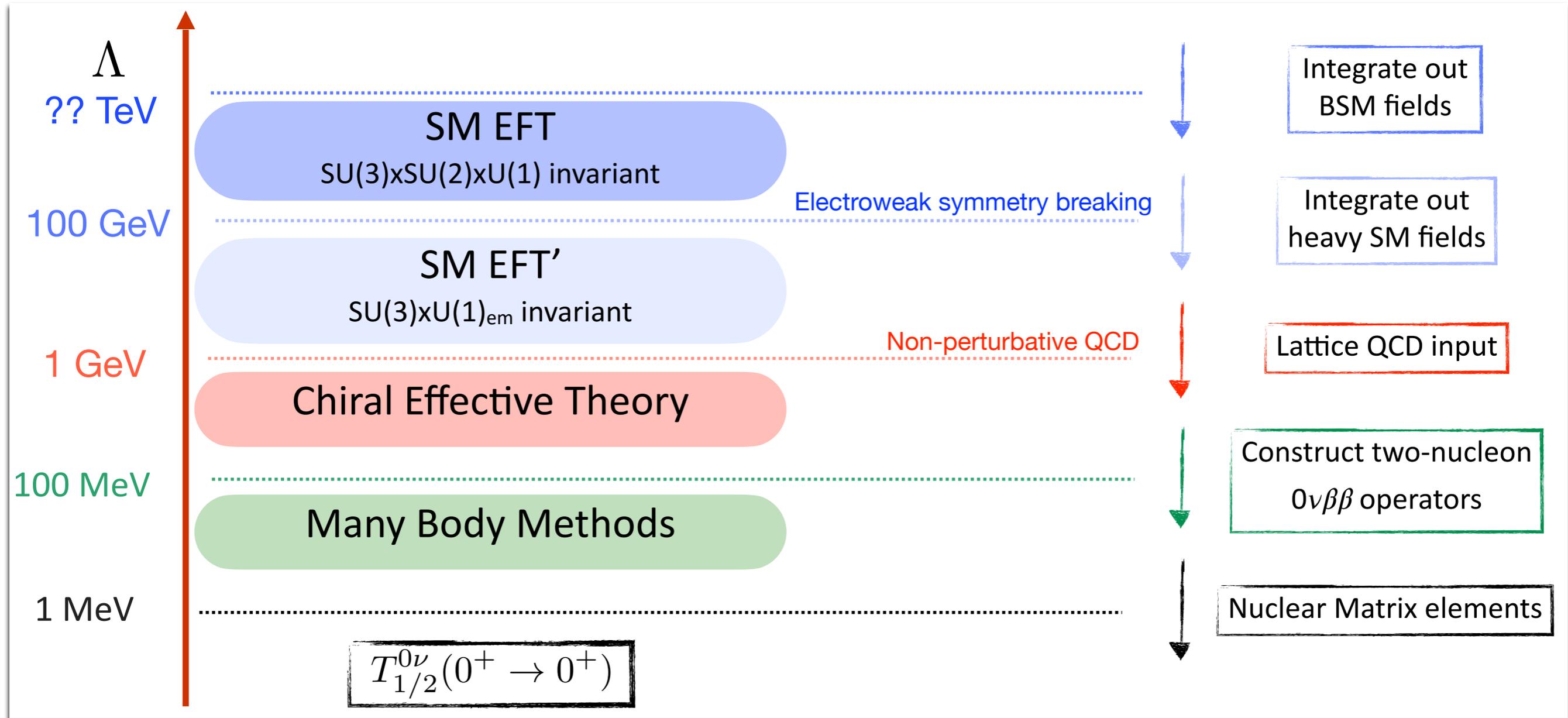
# Sterile neutrinos

Can now go through the same steps as before:



# Sterile neutrinos

Can now go through the same steps as before:



- EFT now includes  $\nu_R$  as explicit degrees of freedom
- LECs and NMEs now depend on  $m_{\nu_R}$
- When/if  $\nu_R$  can be integrated out depends on  $m_{\nu_R}$

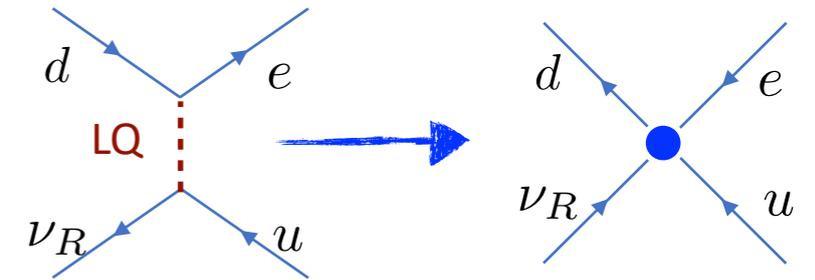
# Sterile neutrinos

## Toy model

- SM + a sterile neutrino + a leptoquark

$$\mathcal{L}_{\text{LQ}} = -y_{ab}^{RL} \bar{d}_{Ra} \tilde{R}^i \epsilon^{ij} L_{Lb}^j + y_{ab}^{\overline{LR}} \bar{Q}_{La}^i \tilde{R}^i \nu_{Rb} + \text{h.c.},$$

- Cannot reproduce neutrino masses/mixings



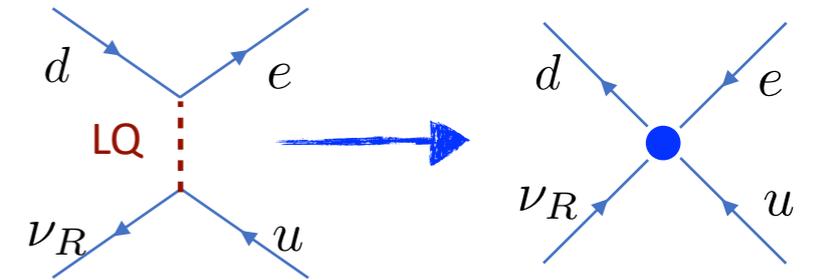
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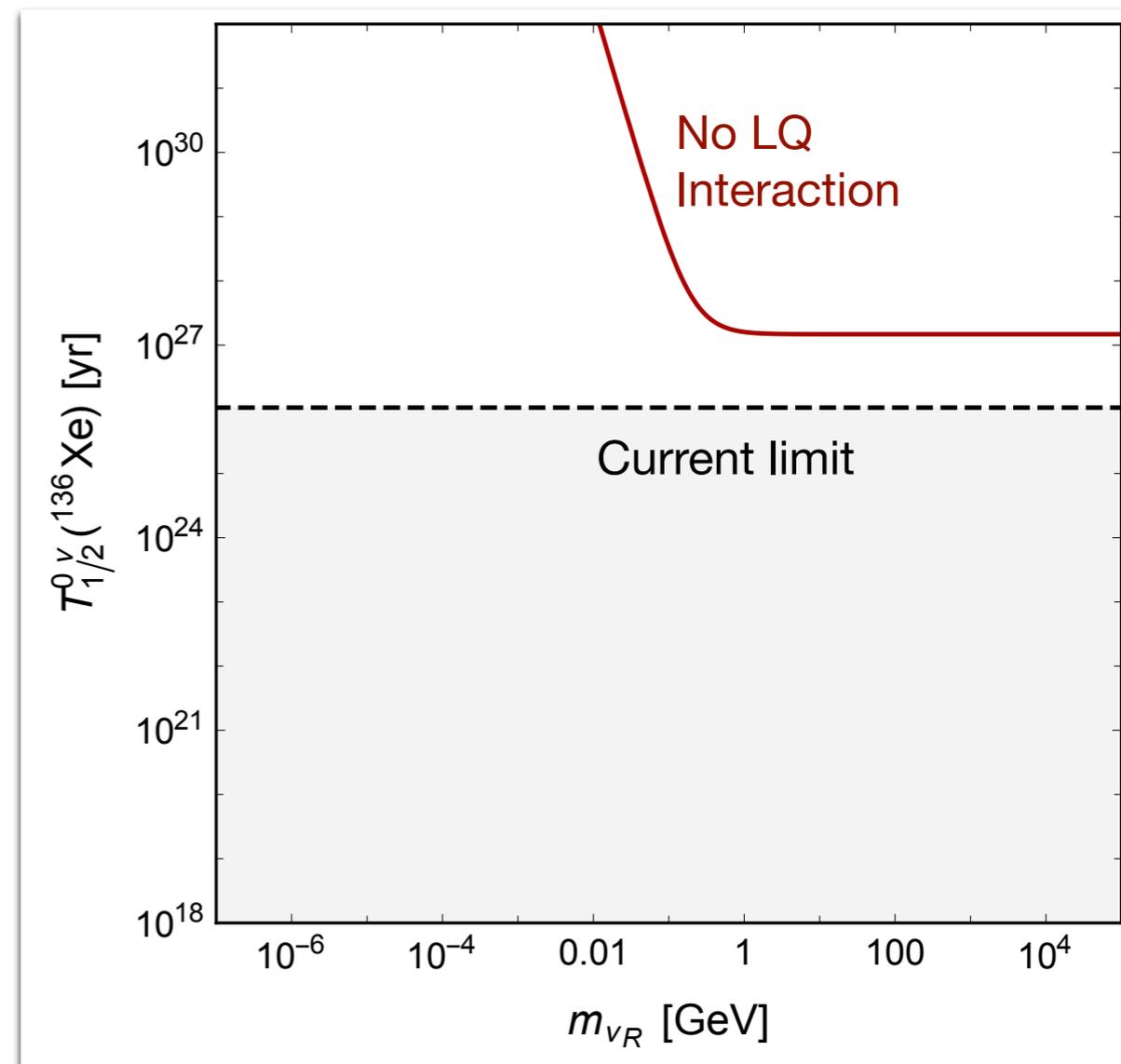
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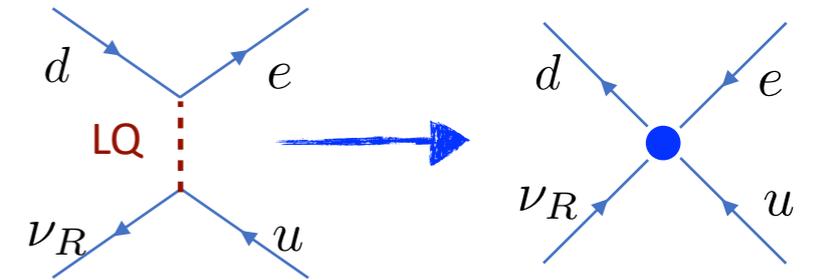
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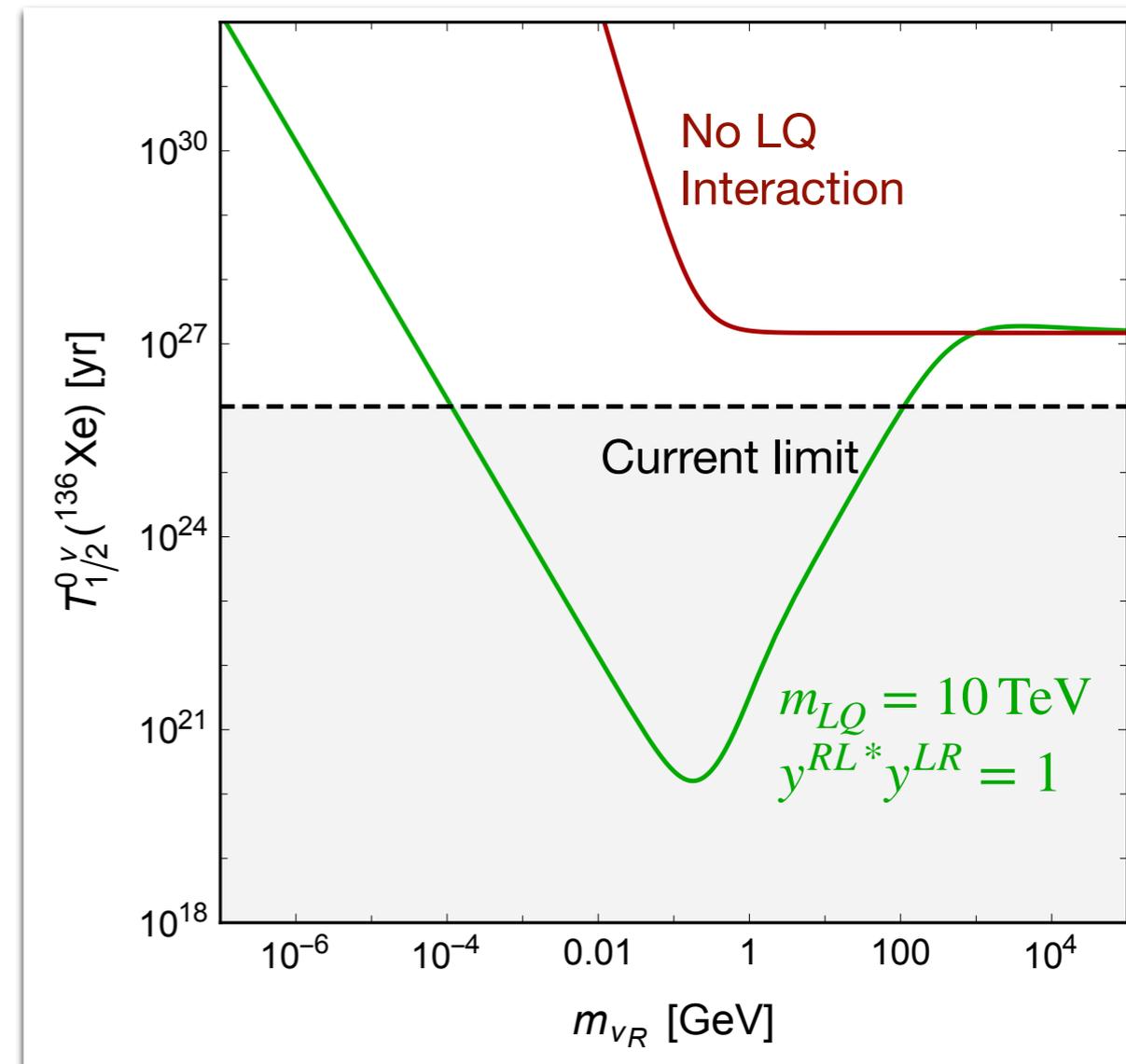
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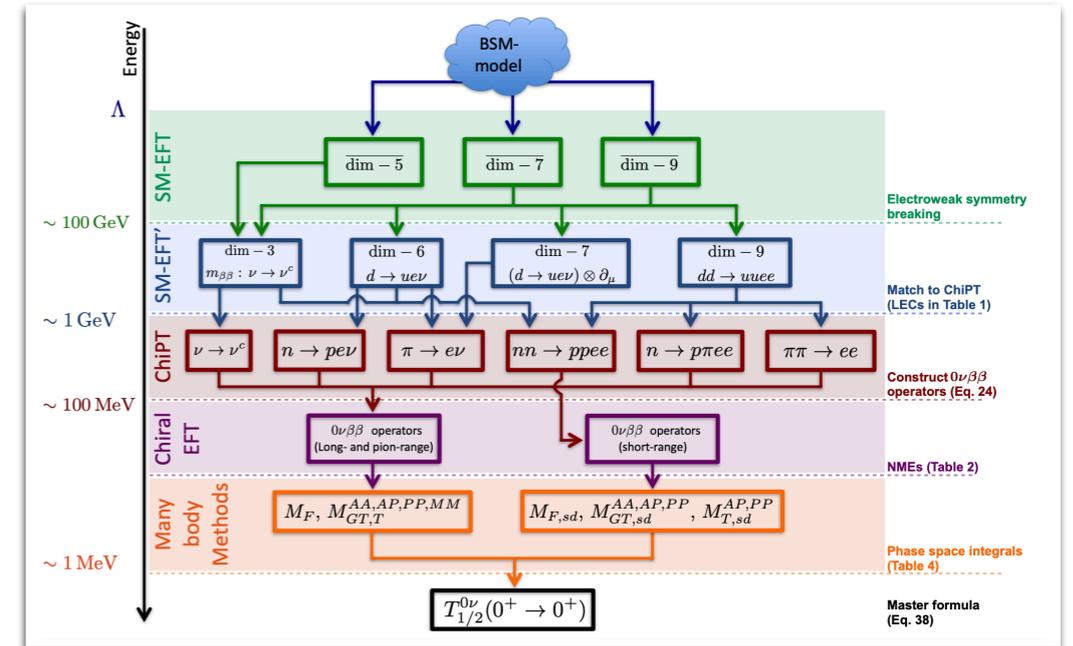
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- Non-standard interactions have a large effect
- Similar large effects in more realistic models



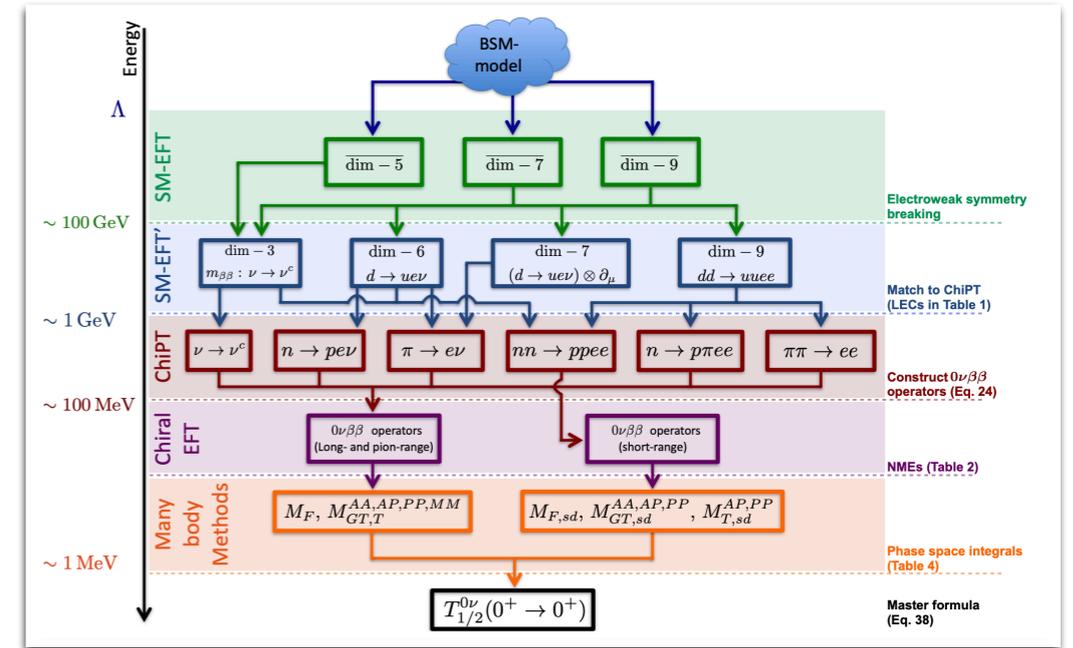
# Summary

- EFTs allow one to systematically describe  $\Delta L=2$  sources
- Light Majorana neutrino exchange (dim-5)
- Dimension-7 & -9 sources
- Effects from  $\nu_R$

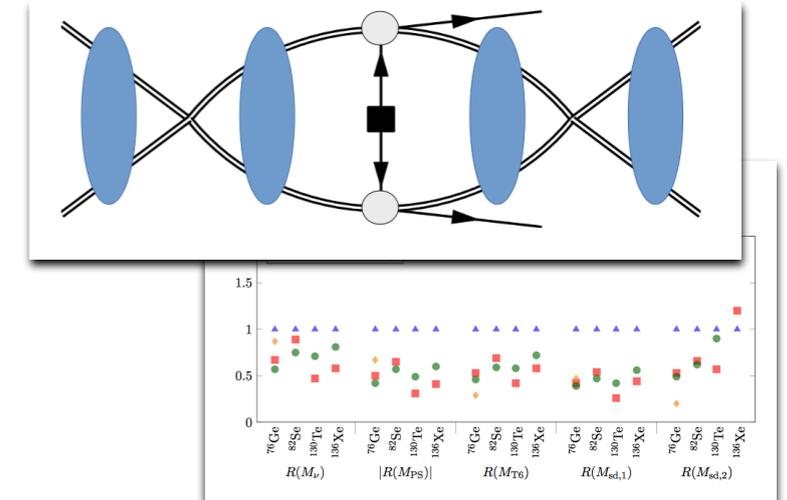


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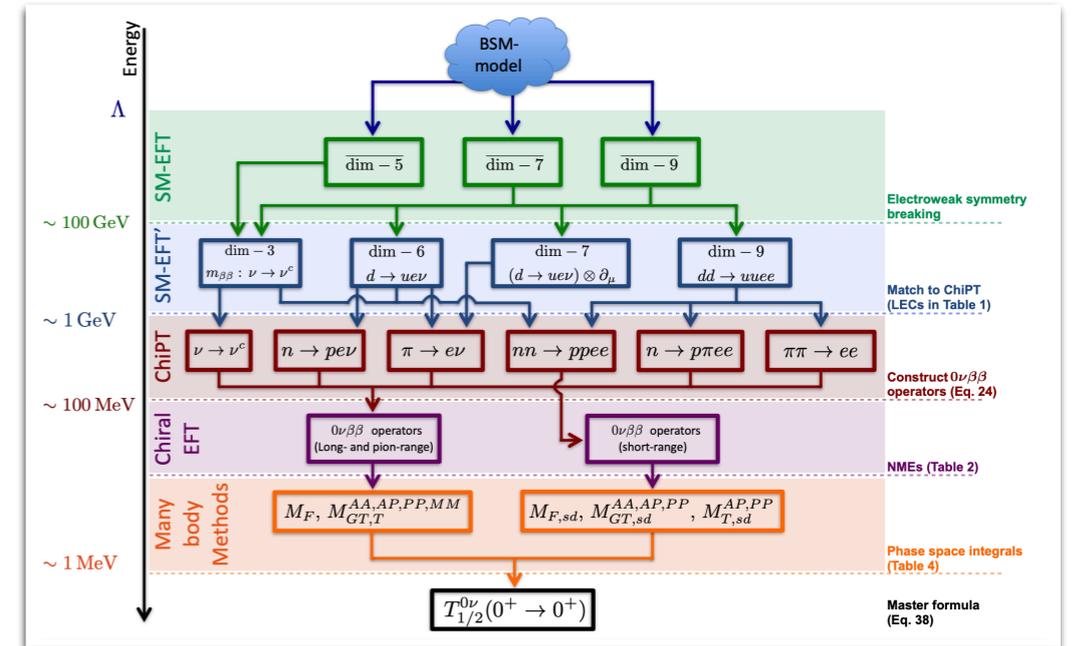


- Matching to chiral EFT involves unknown LECs
- Renormalization requires terms beyond Weinberg counting
- Can in principle be determined from LQCD
- Needed Nuclear Matrix Elements determined in literature

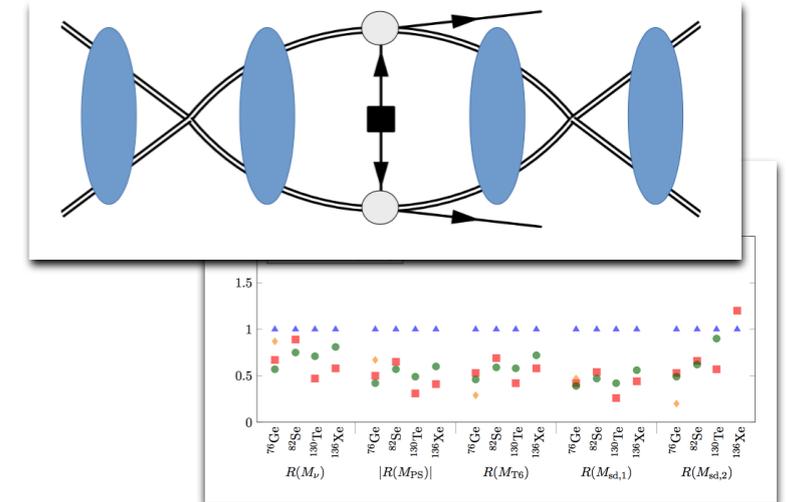


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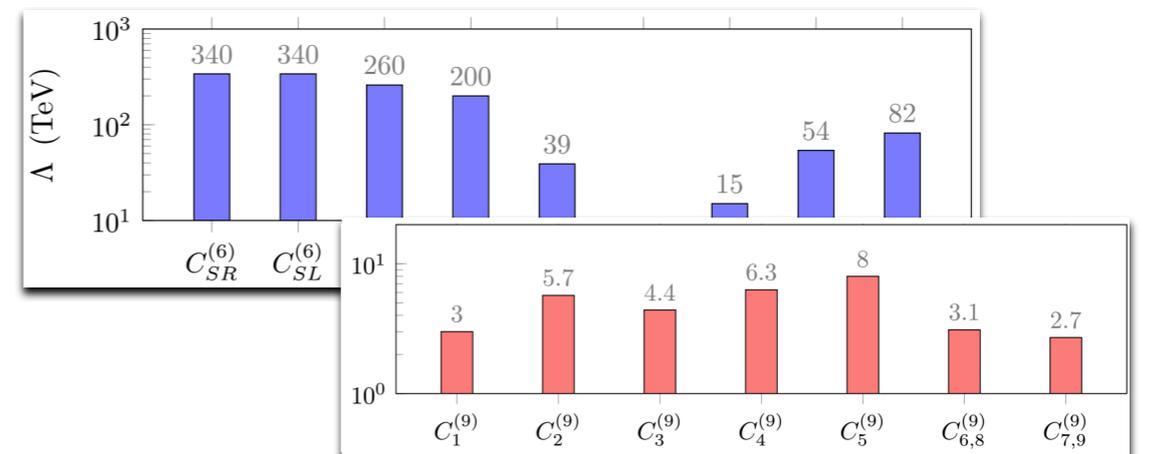
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- $0\nu\beta\beta$  can probe
  - O(1-10) TeV scales for dim-9
  - O(100) TeV scales for dim-7
  - O(10) TeV scales for  $\nu_R$  interactions
- Order 1 LECs + NMEs uncertainties

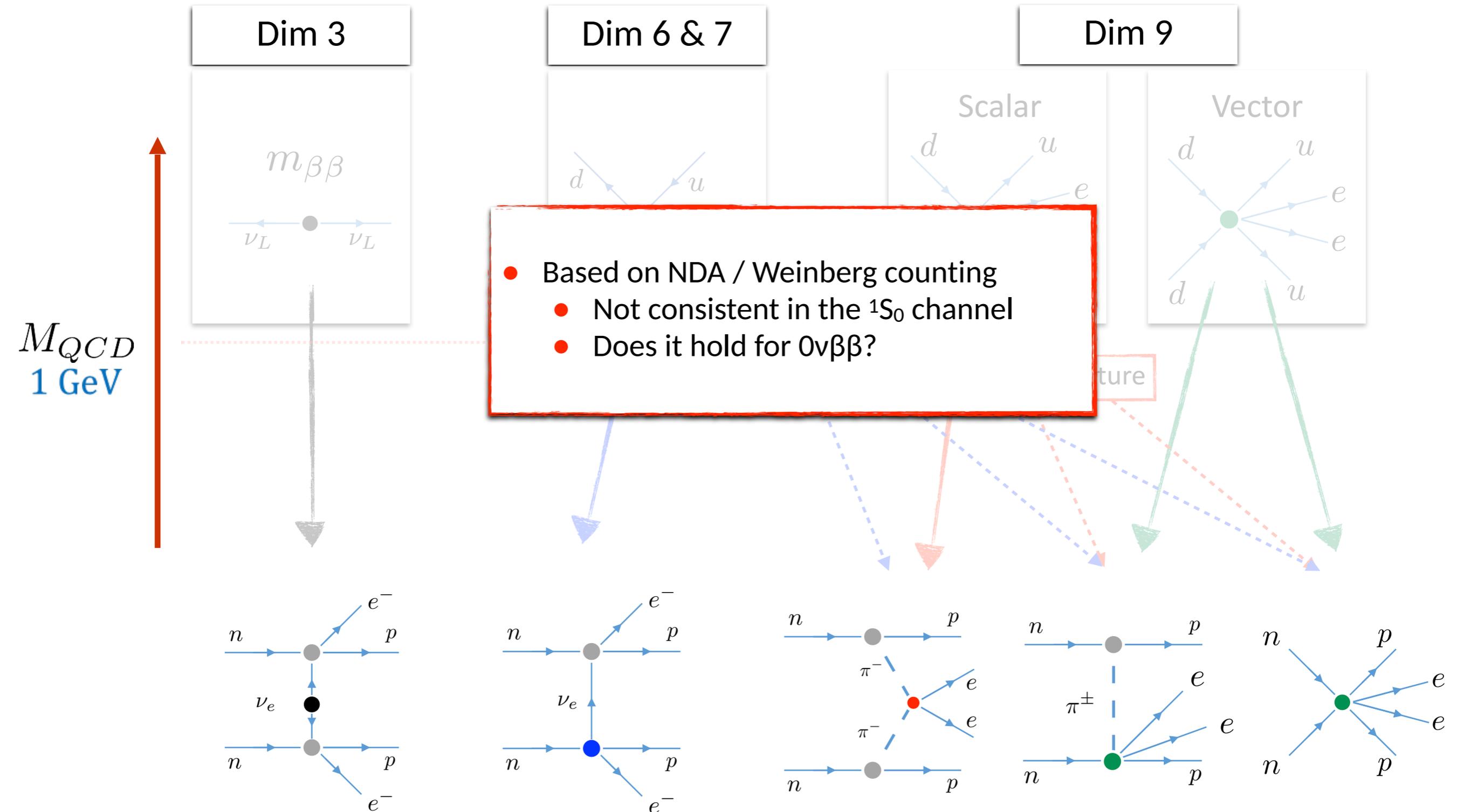


# Back up slides

# A new contact interaction at leading order

# Chiral EFT

## Summary



# Checking the power counting

Dimension-3

Check that  $\mathcal{A}(nn \rightarrow ppee)$  is finite

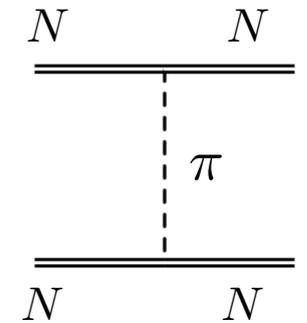
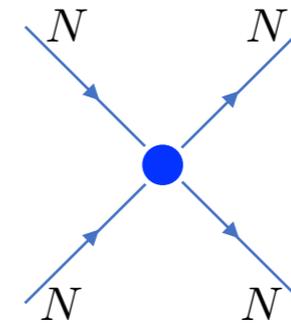
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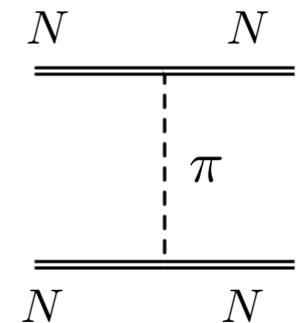
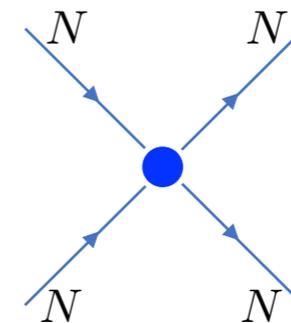
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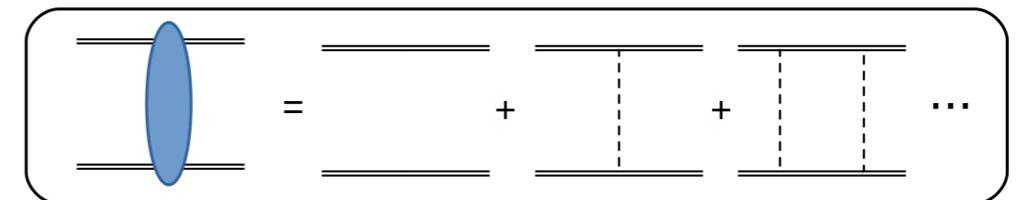
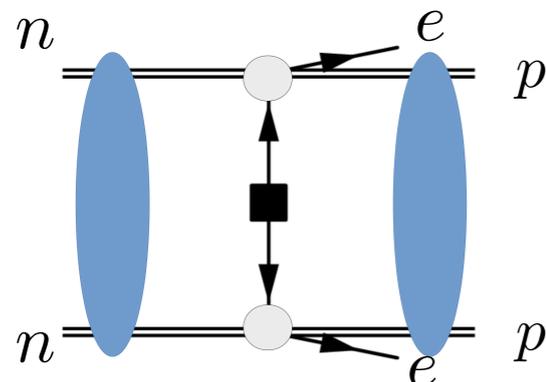
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Dress the  $\Delta L=2$  potential with (renormalized) strong interactions:



✓ finite

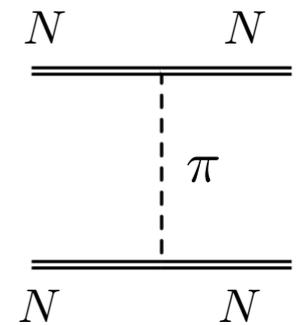
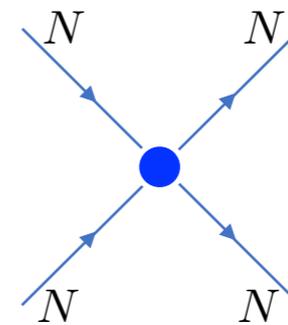
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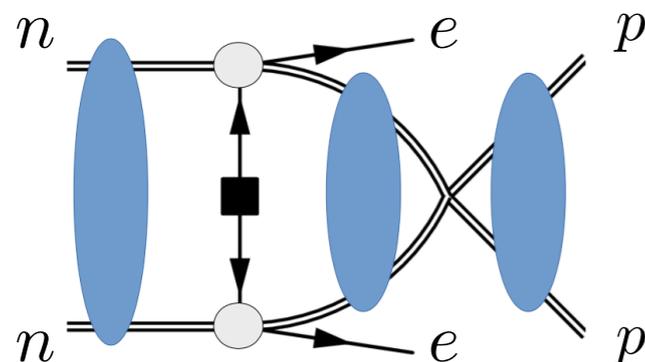
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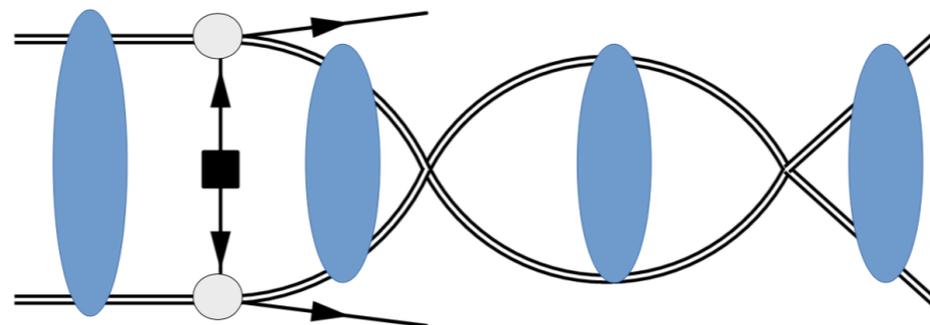
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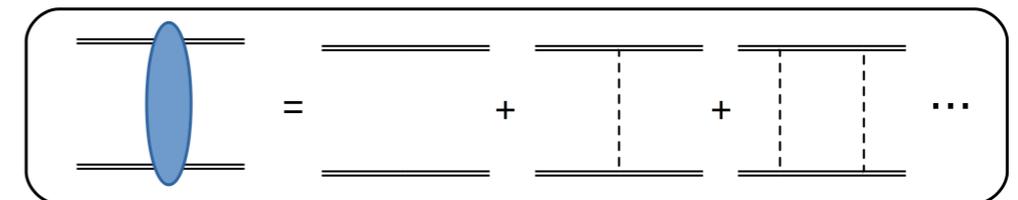


+



+

...



✓ finite

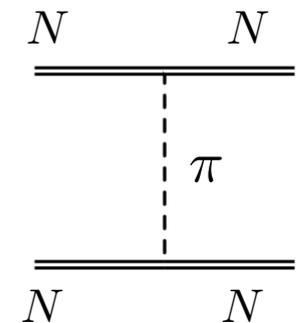
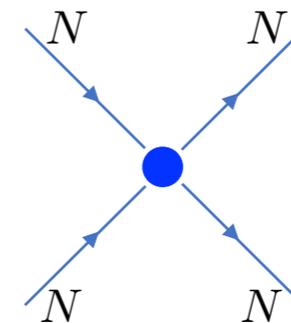
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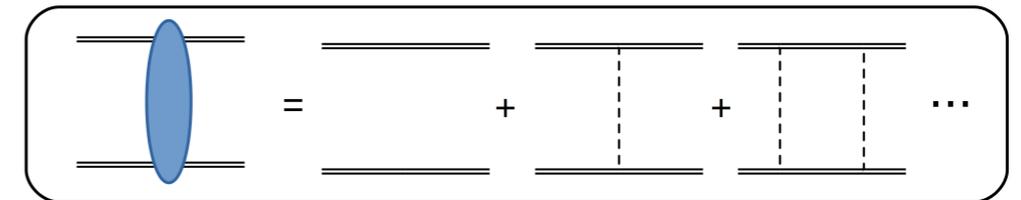
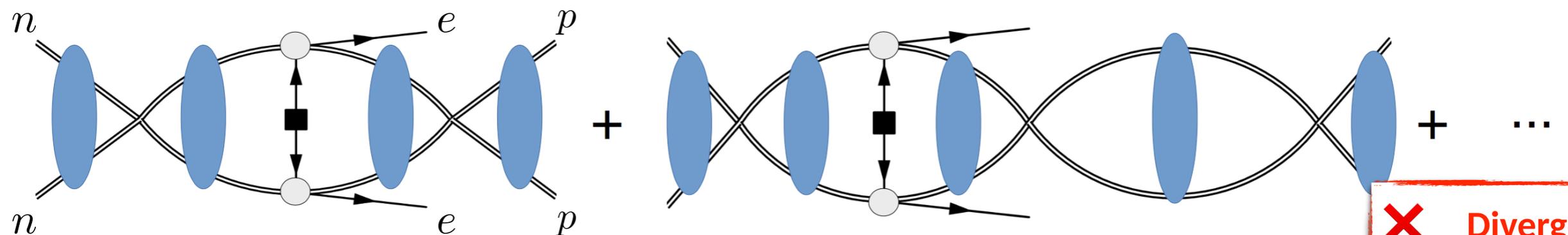
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Dress the  $\Delta L=2$  potential with (renormalized) strong interactions:



**✗ Divergent**

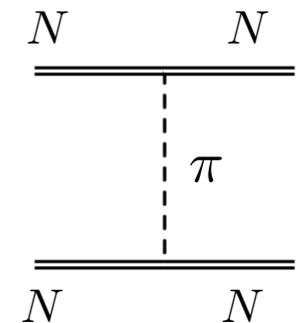
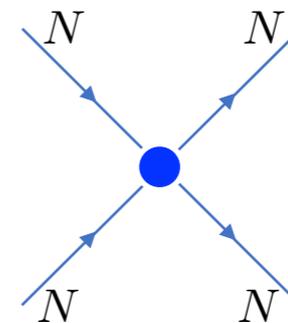
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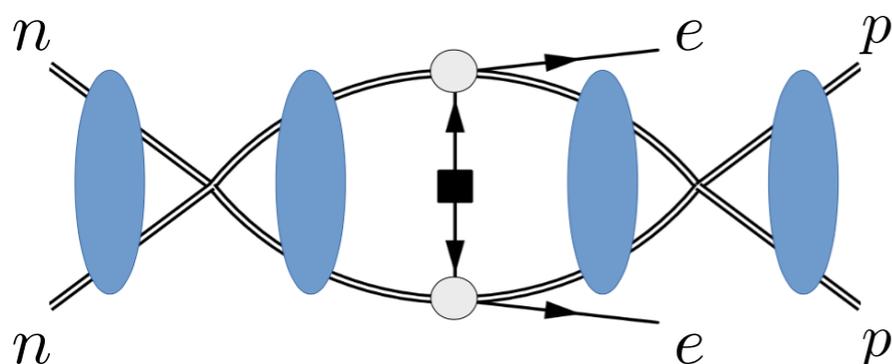
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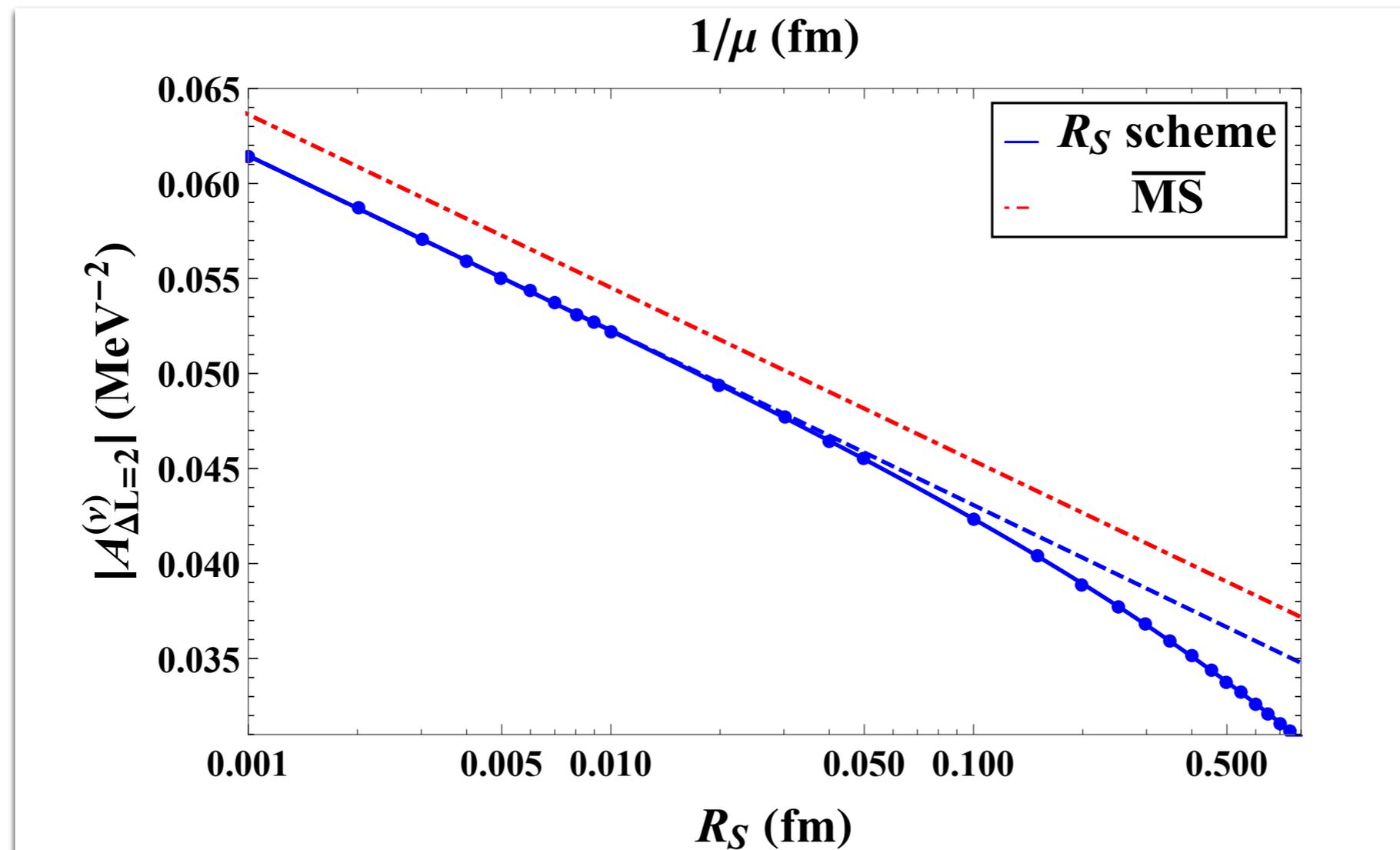
In MS-bar:



$$= - \left( \frac{m_N}{4\pi} \right)^2 (1 + 2g_A^2) \frac{1}{2} \left( \log \frac{\mu^2}{-(|\mathbf{p}| + |\mathbf{p}'|)^2 + i0^+} + 1 \right) + \text{finite}$$

Regulator dependent

# Numerical results



- Amplitudes obtained using
  - MS-bar
  - Coordinate-space cut-off

$$\tilde{C} \delta^{(3)}(\mathbf{r}) \rightarrow \frac{\tilde{C}(R_S)}{(\sqrt{\pi}R_S)^3} \exp\left(-\frac{r^2}{R_S^2}\right)$$

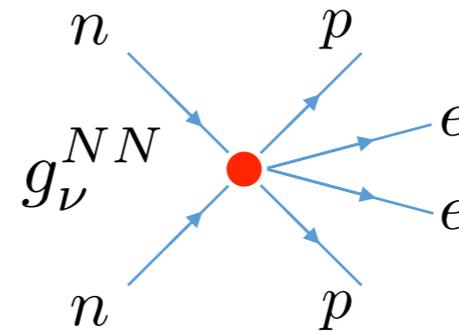
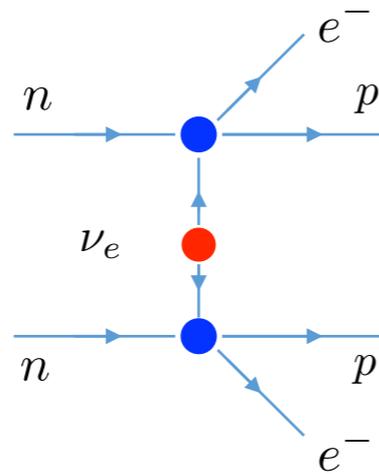
- Clear  $\mu$  or  $R_S$  dependence

# Need for a counter term

- Need a new contact interaction at leading order to get physical amplitudes:

$$\mathcal{L}_{CT} = 2G_F^2 V_{ud}^2 m_{\beta\beta} g_\nu^{NN} \bar{p}n \bar{p}n \bar{e}_L C \bar{e}_L^T$$

$$V_{\Delta L=2} = V_\nu + V_{\nu,CT} =$$

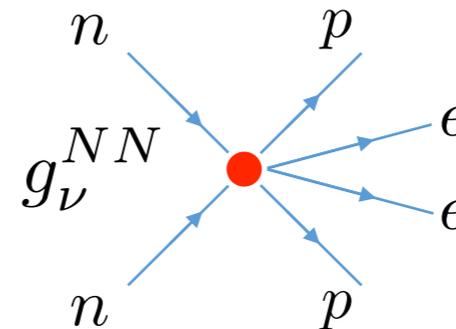
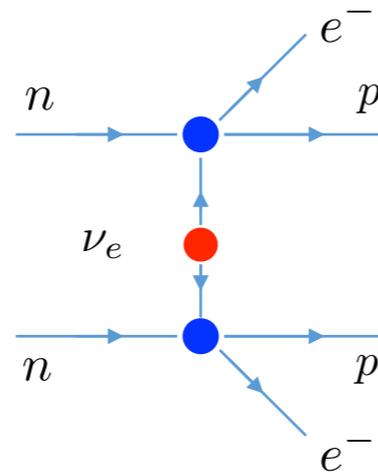


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$$V_{\Delta L=2} = V_\nu + V_{\nu,CT} =$$



- Finite part of  $g_\nu^{NN}$  is currently unknown, hard to estimate its impact

- Could be determined from a lattice calculation of  $\mathcal{A}(nn \rightarrow ppe^- e^-)$

- Area of active research

Davoudi and Kadam, '20; Feng et al, '20

- Estimate from relation to EM (back-up slides)

- ~10-30% contribution in  $\mathcal{A}(nn \rightarrow ppe^- e^-)$

- ~60% in light nuclei,  $^{12}\text{Be} \rightarrow ^{12}\text{C} e^- e^-$

# Checking the Weinberg counting

Any effect for the dim-6,7,9 terms?

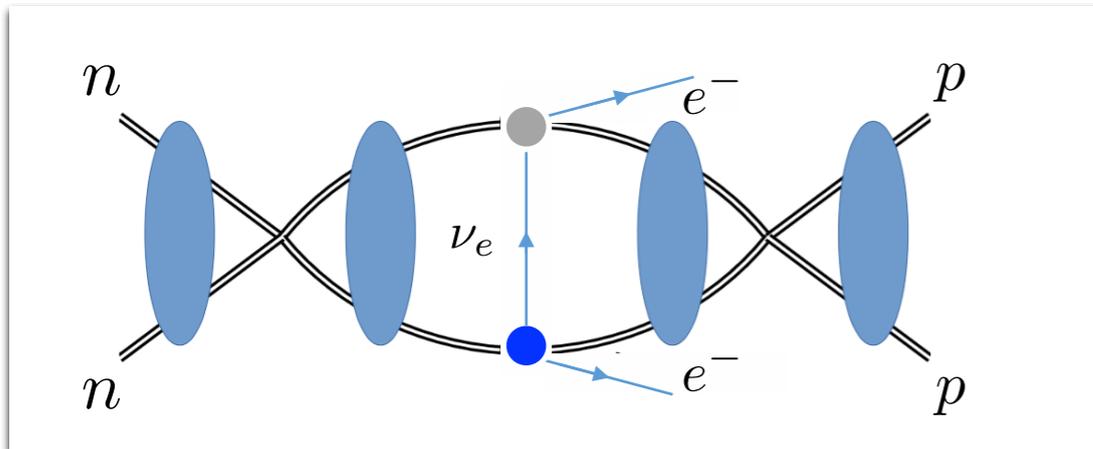
- In the Majorana-mass case, the LNV potential leads to a divergence
- Can perform the same checks for the higher-dimensional terms

# Checking the Weinberg counting

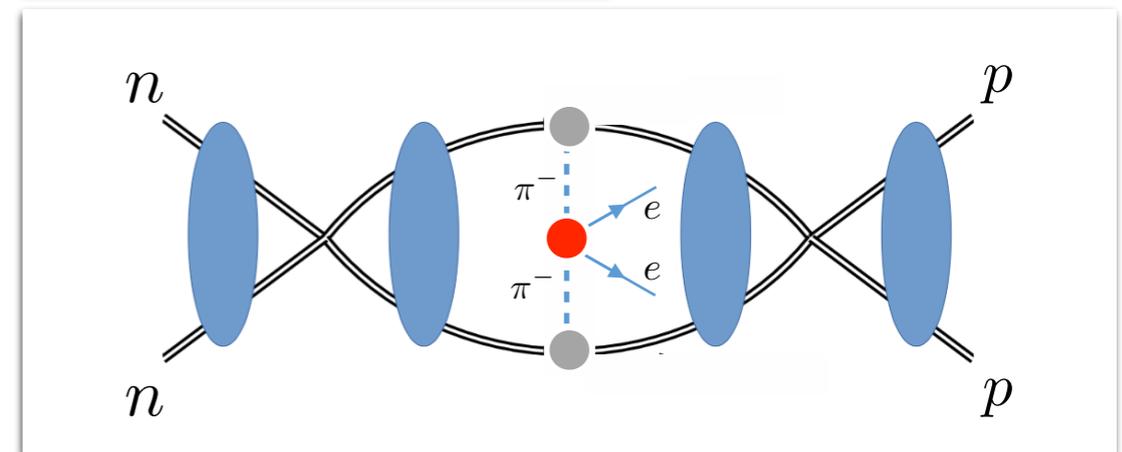
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Dim-6:  $C_{VL,VR}^{(6)}$



Dim-9:  $C_{1-9}^{(9)}$

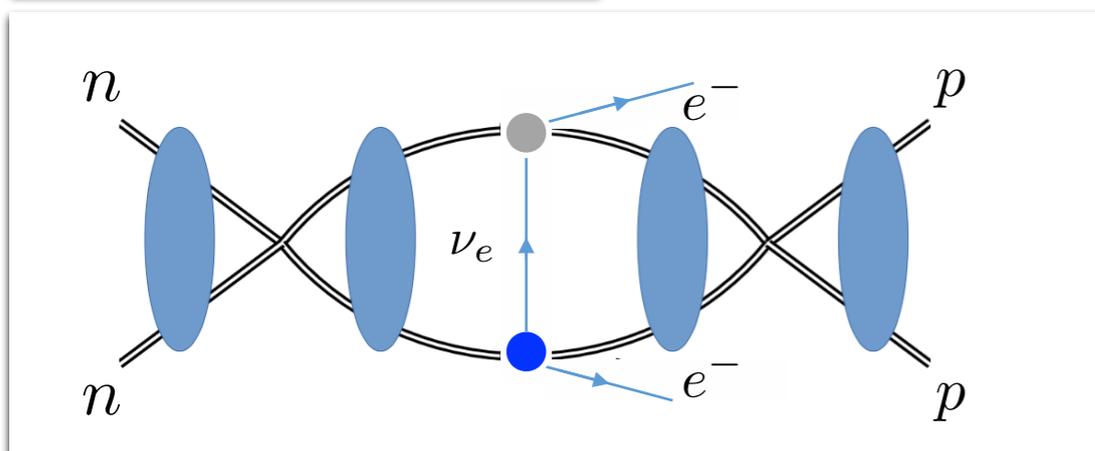


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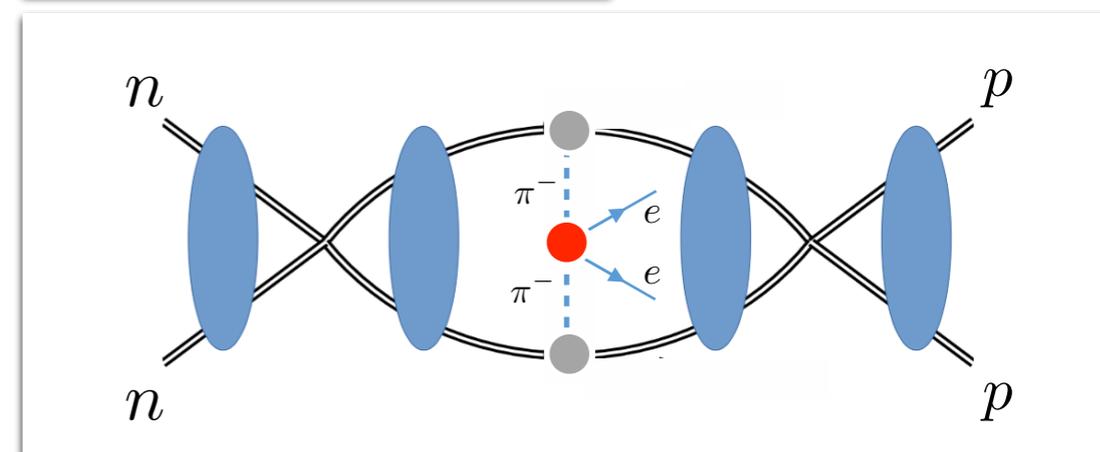
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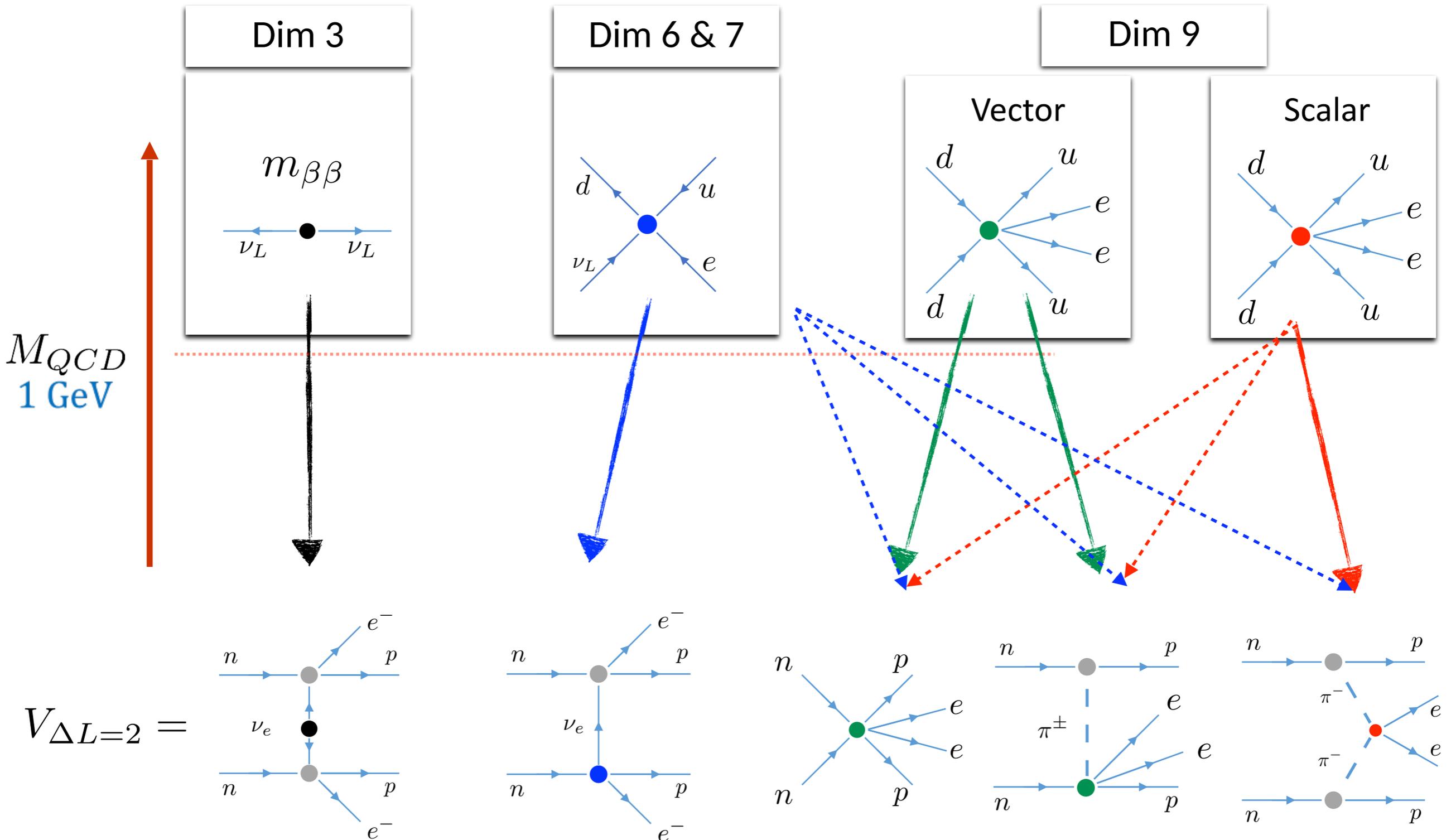
Dim-9:  $C_{1-9}^{(9)}$



- Need to include contact interactions at LO in these cases
  - Often disagrees with the Weinberg / NDA counting

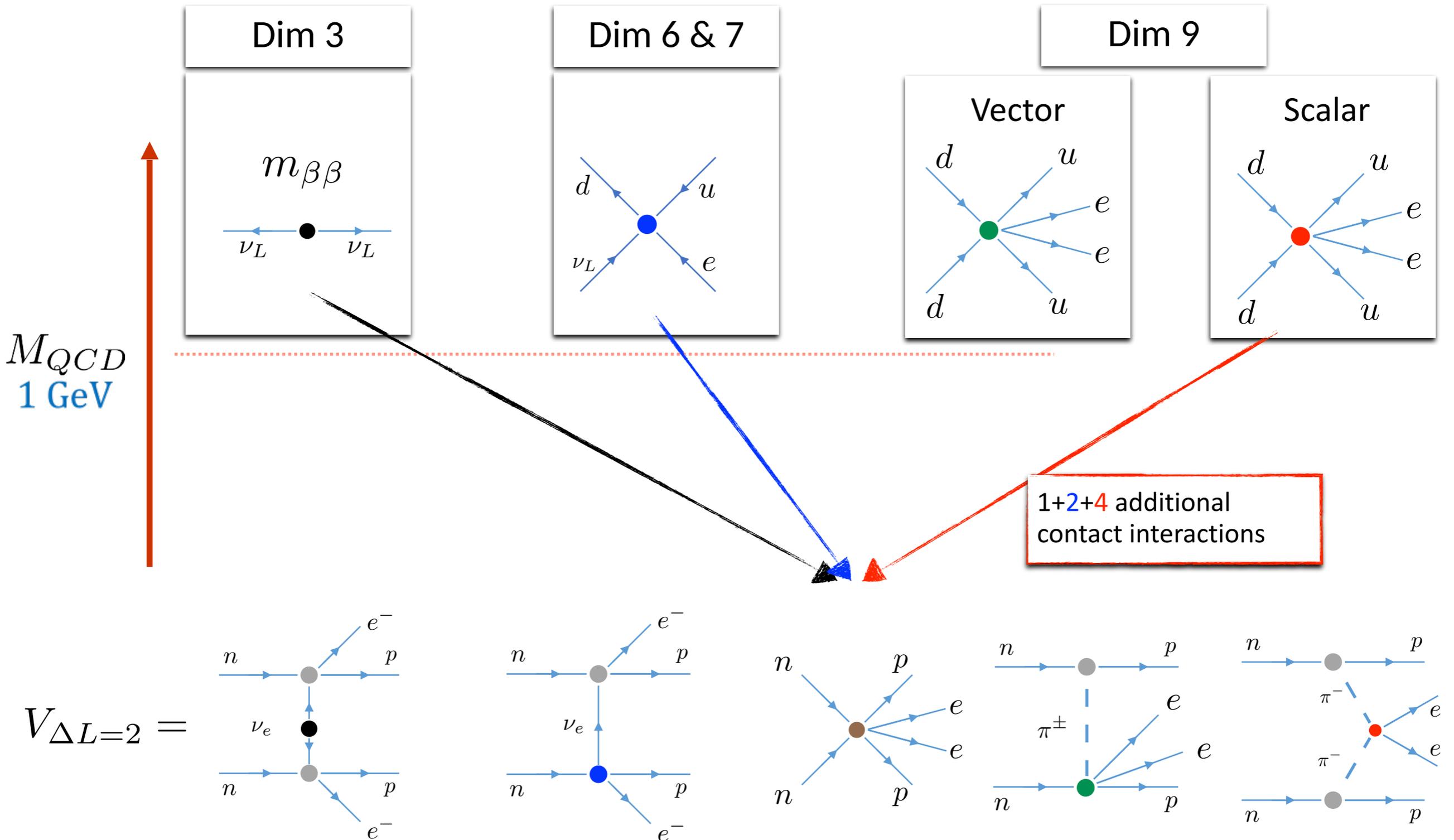
# Chiral EFT

NDA / Weinberg



# Chiral EFT

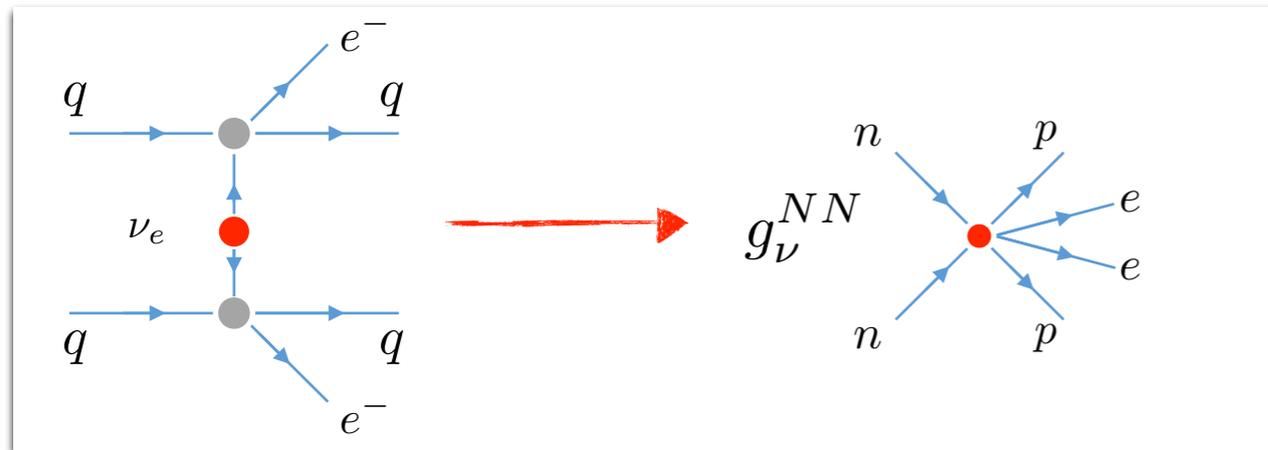
Beyond NDA / Weinberg



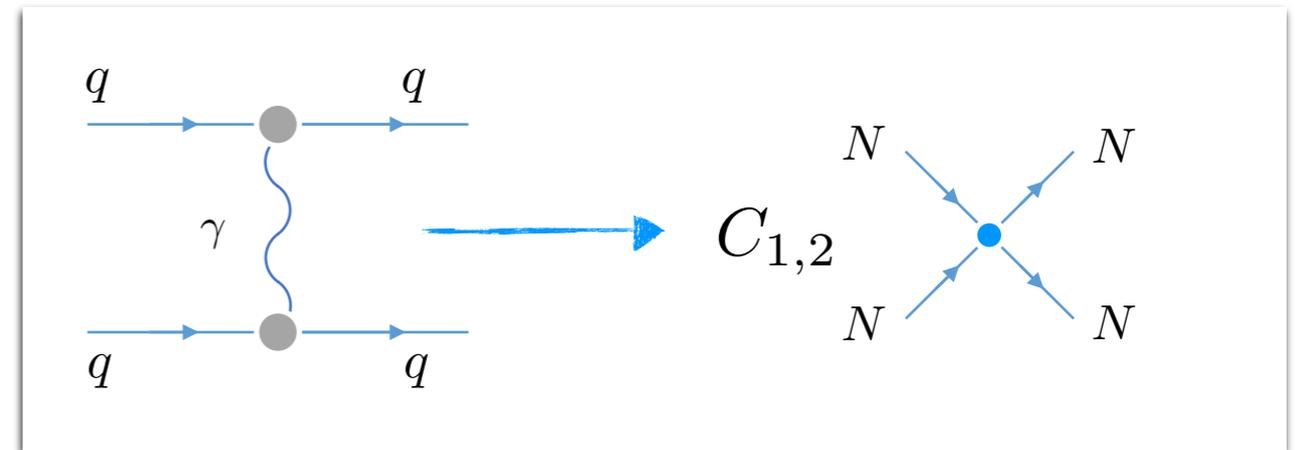
# Relation to electromagnetism

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LNV contact term

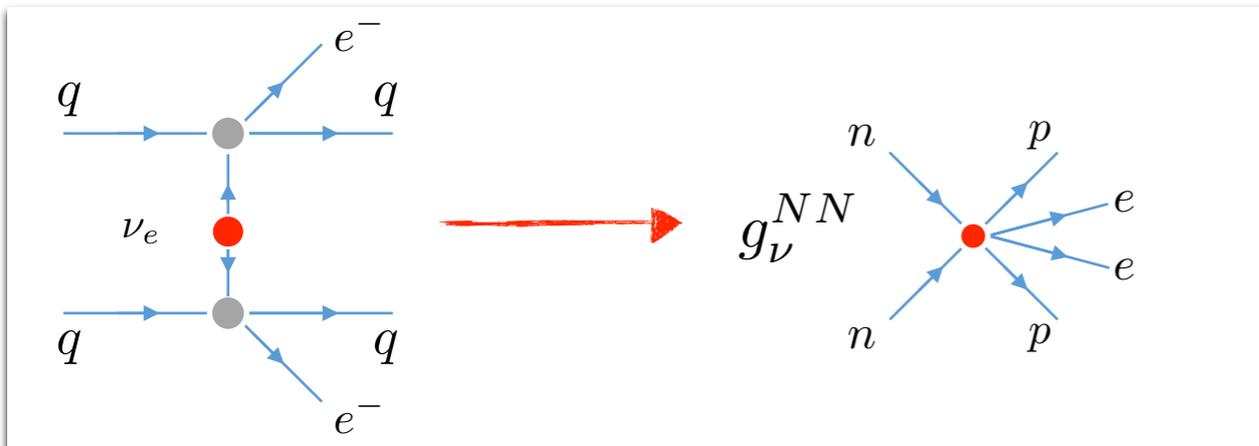


EM contact term



# Relation to electromagnetism

## LNV contact term



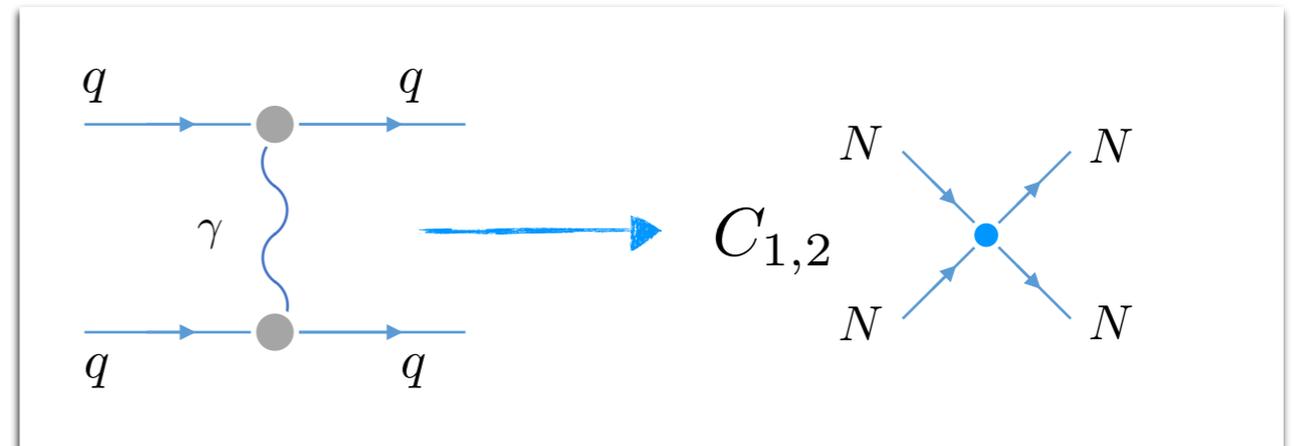
- Hard part of two Weak currents

$$\sim G_F^2 m_{\beta\beta} \langle NN | J_L^\mu(x) J_{L\mu}(y) | NN \rangle$$

$$\times \int \frac{d^4 q}{(2\pi)^4} \frac{e^{iq \cdot (x-y)}}{q^2}$$

- Leptonic part combines to boson propagator

## EM contact term



- Hard part of two EM currents

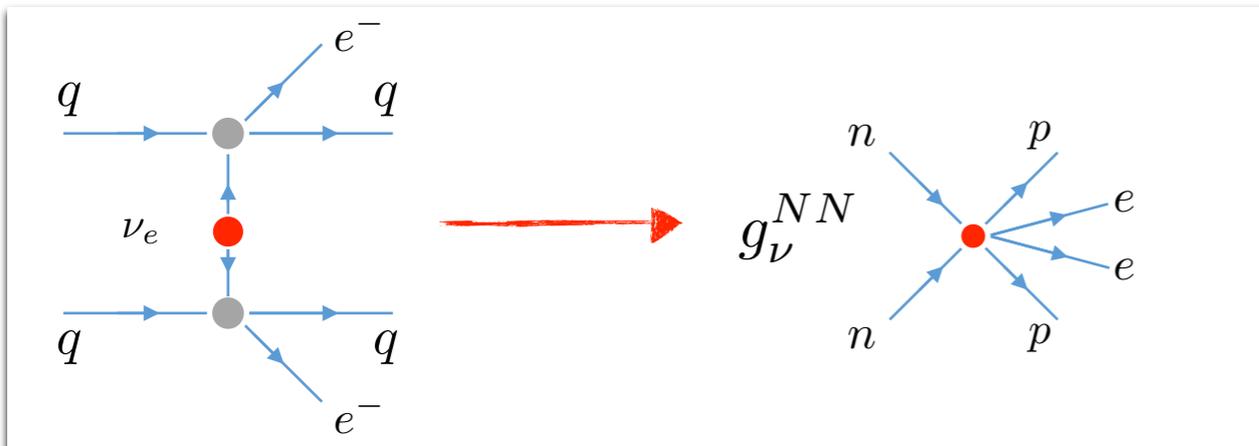
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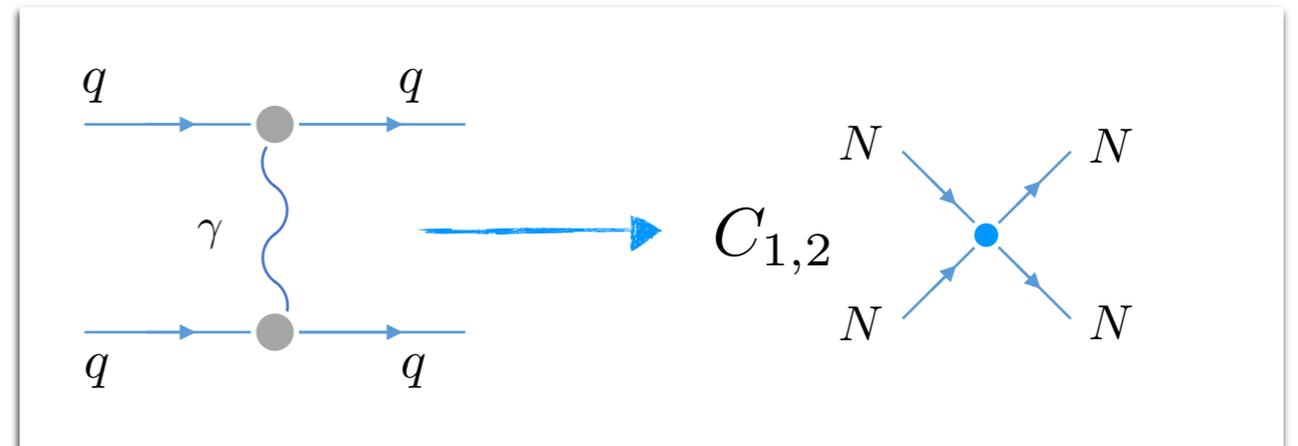
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- Non-hadronic part is the photon propagator

The appearance of the photon propagator allows one to relate the two!

# Relation to electromagnetism

- Only two  $\Delta I=2$  operators can be induced

$$O_1 = \bar{N} Q_L N \bar{N} Q_L N - \frac{\text{Tr } Q_L^2}{6} \bar{N} \vec{\tau} N \bar{N} \vec{\tau} N + (L \rightarrow R)$$

$$O_2 = \bar{N} Q_L N \bar{N} Q_R N - \frac{\text{Tr } Q_L Q_R}{6} \bar{N} \vec{\tau} N \bar{N} \vec{\tau} N + (L \leftrightarrow R)$$

with spurions

$$Q_L = u^\dagger Q_L u, \quad Q_R = u Q_R u^\dagger,$$

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EM

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$$Q_L = Q_R = \tau^3/2$$

LNV

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Chiral symmetry

$$g_\nu^{NN} = C_1$$

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$$O_2 = \bar{N} Q_L N \bar{N} Q_R N - \frac{\text{Tr } Q_L Q_R}{6} \bar{N} \vec{\tau} N \bar{N} \vec{\tau} N + (L \leftrightarrow R)$$

with spurions

$$Q_L = u^\dagger Q_L u, \quad Q_R = u Q_R u^\dagger,$$

$$u = \exp(i\pi \cdot \tau / 2F_\pi)$$

EM

$$\mathcal{L}_{em} = e^2/4 (C_1 O_1 + C_2 O_2)$$

$$Q_L = Q_R = \tau^3/2$$

- EM induces an extra term
  - Equivalent up to 2 pions
  - Hard to disentangle

LNV

$$\mathcal{L}_{LNV} = g_\nu^{NN} G_F^2 m_{\beta\beta} O_1 \bar{e} e^c$$

$$Q_L = \tau^+, \quad Q_R = 0$$

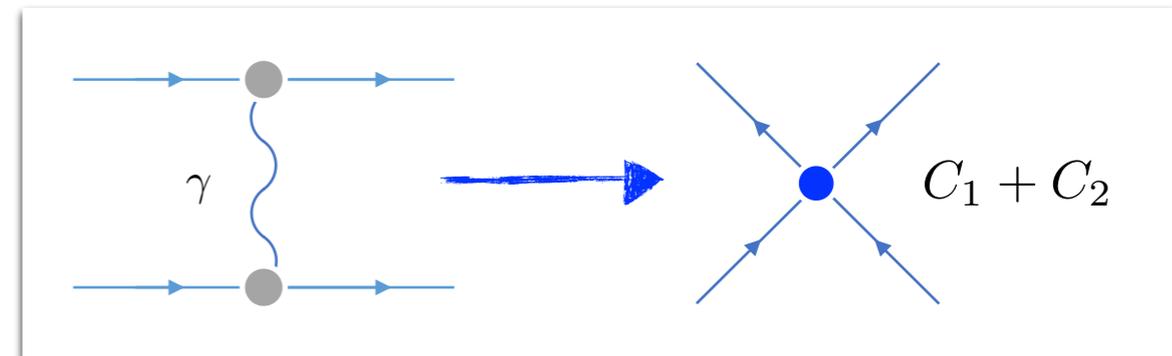
Chiral symmetry

$$g_\nu^{NN} = C_1$$

# Relation to electromagnetism

- $\Delta I=2$  in NN scattering

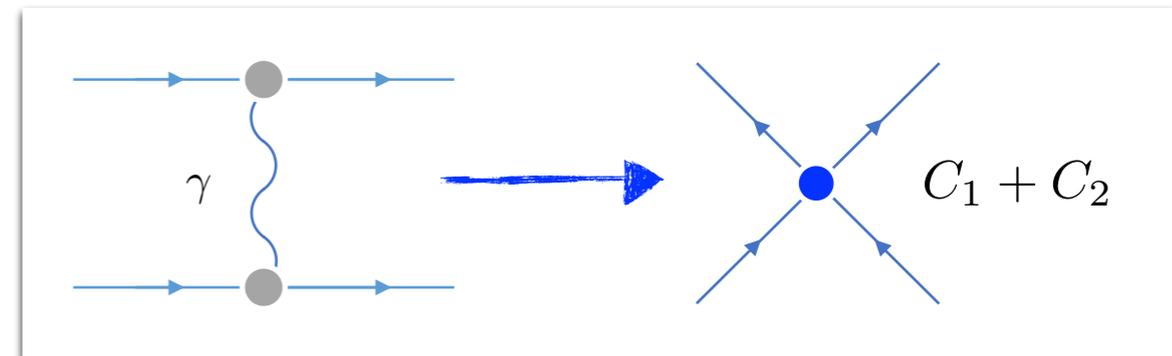
- Charge-independence breaking  $(a_{nn} + a_{pp})/2 - a_{np}$ 
  - From photon exchange & the pion mass difference
  - $C_1 + C_2$  (needed at LO in isospin breaking)



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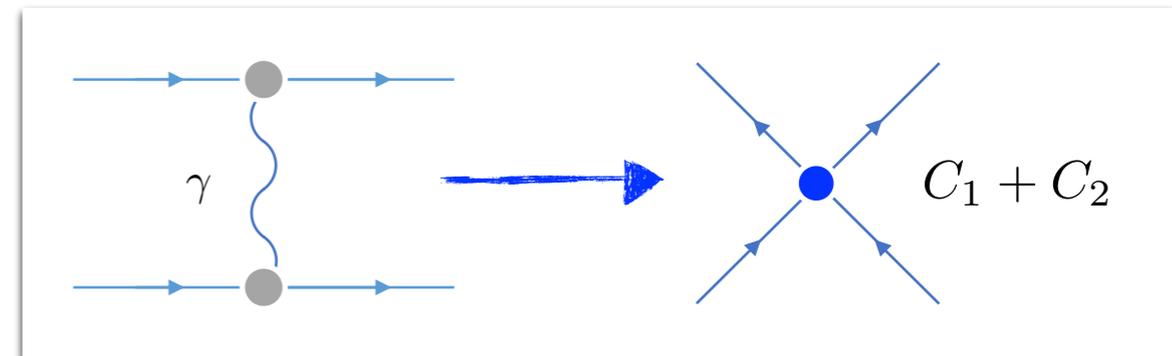


- Allows an estimate of  $g_\nu^{NN}$ 
  - Extract  $C_1 + C_2$  from CIB
  - Assume  $g_\nu^{NN}(\mu) = \frac{C_1(\mu) + C_2(\mu)}{2}$
  - Roughly 10% effect for  $R_s = 0.6$  fm
  - Uncontrolled error

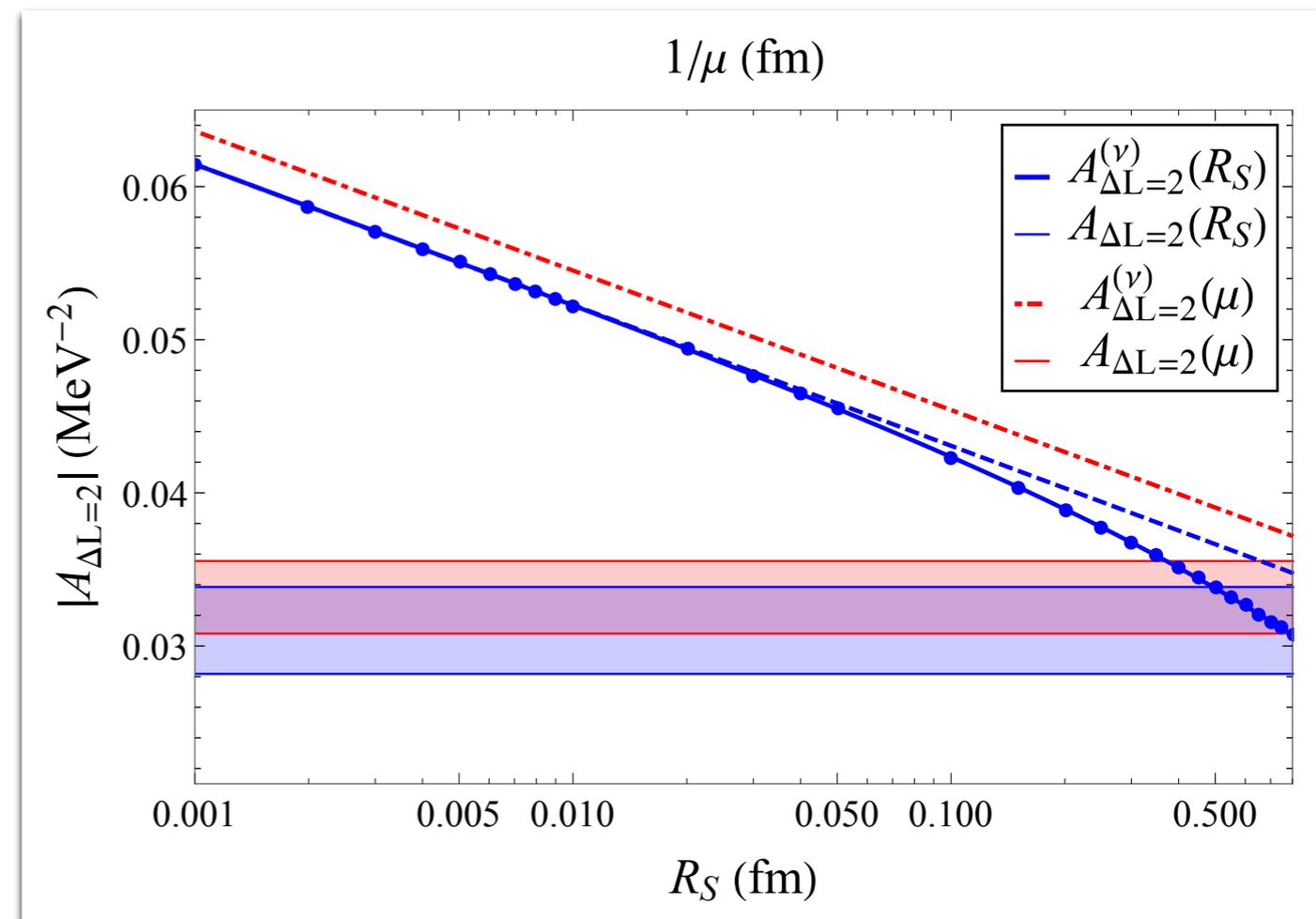
# Relation to electromagnetism

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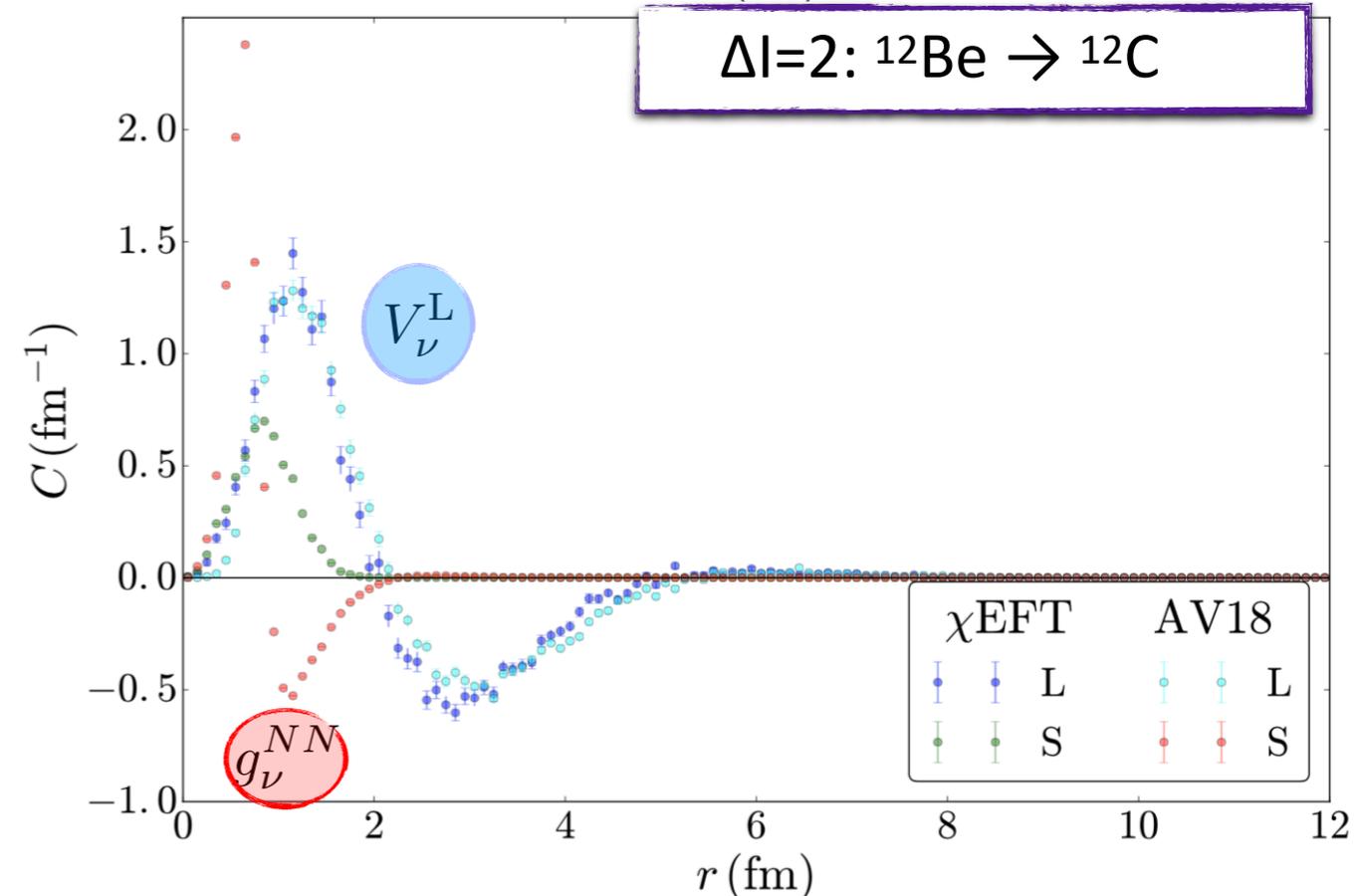
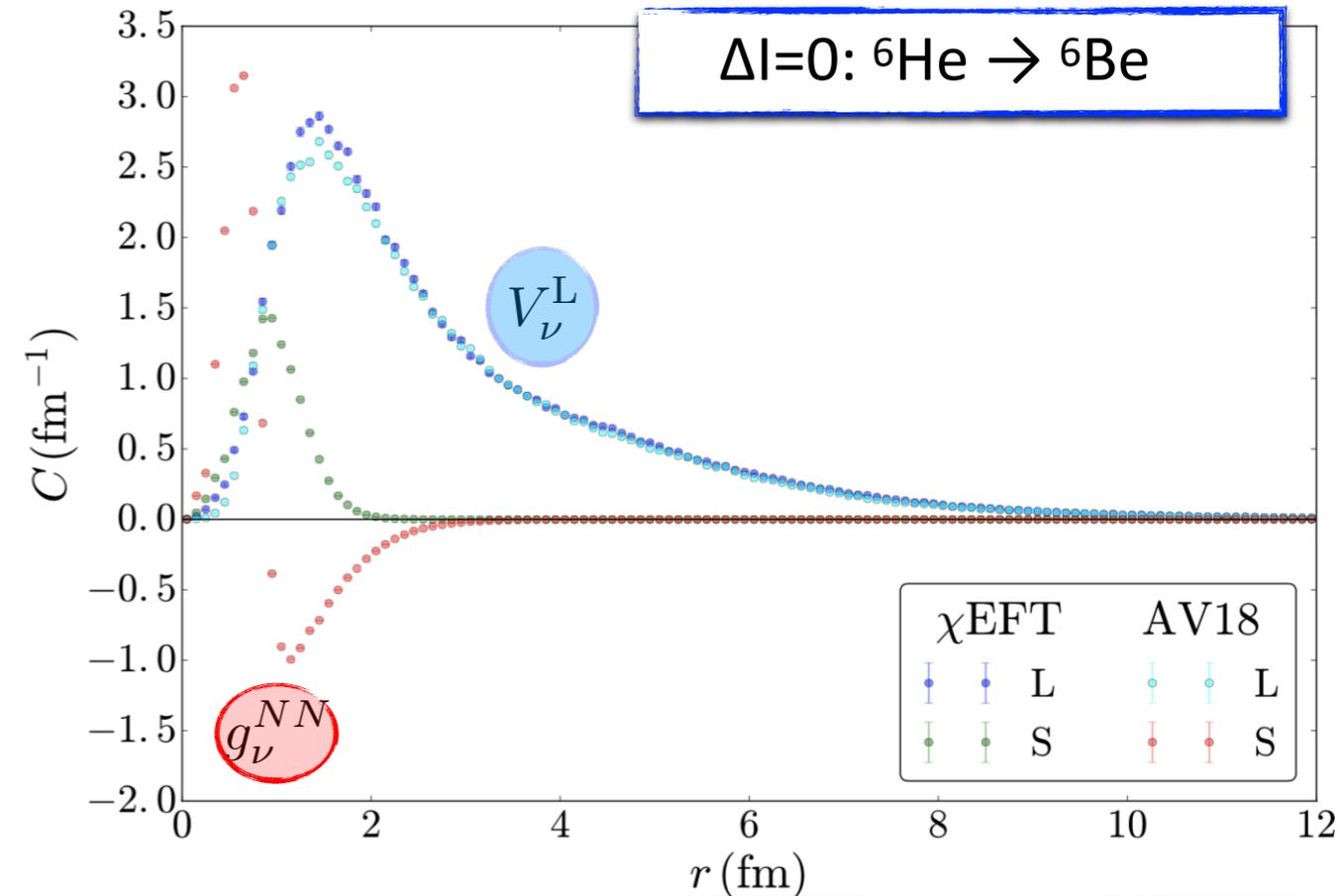
# Estimate of impact in light nuclei

# Estimate of impact

## Light nuclei

M. Piarulli, R. Wiringa, S. Pastore

- Combine estimate  $g_\nu = (C_1 + C_2)/2$
- With wavefunctions:
  - From Chiral potential  
M. Piarulli et. al. '16
  - Obtained from AV18 potential  
R. Wiringa, Stoks, Schiavilla, '95



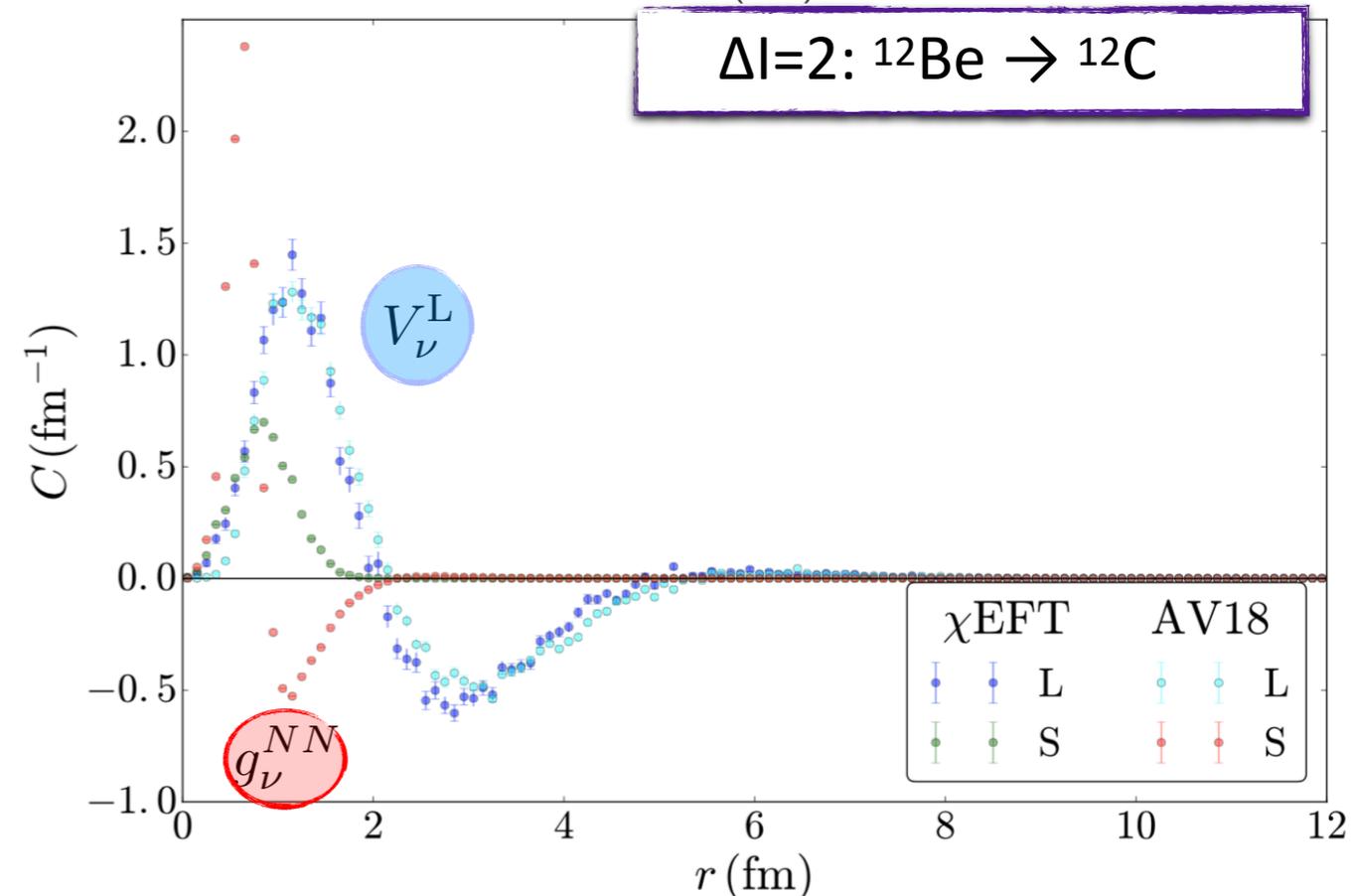
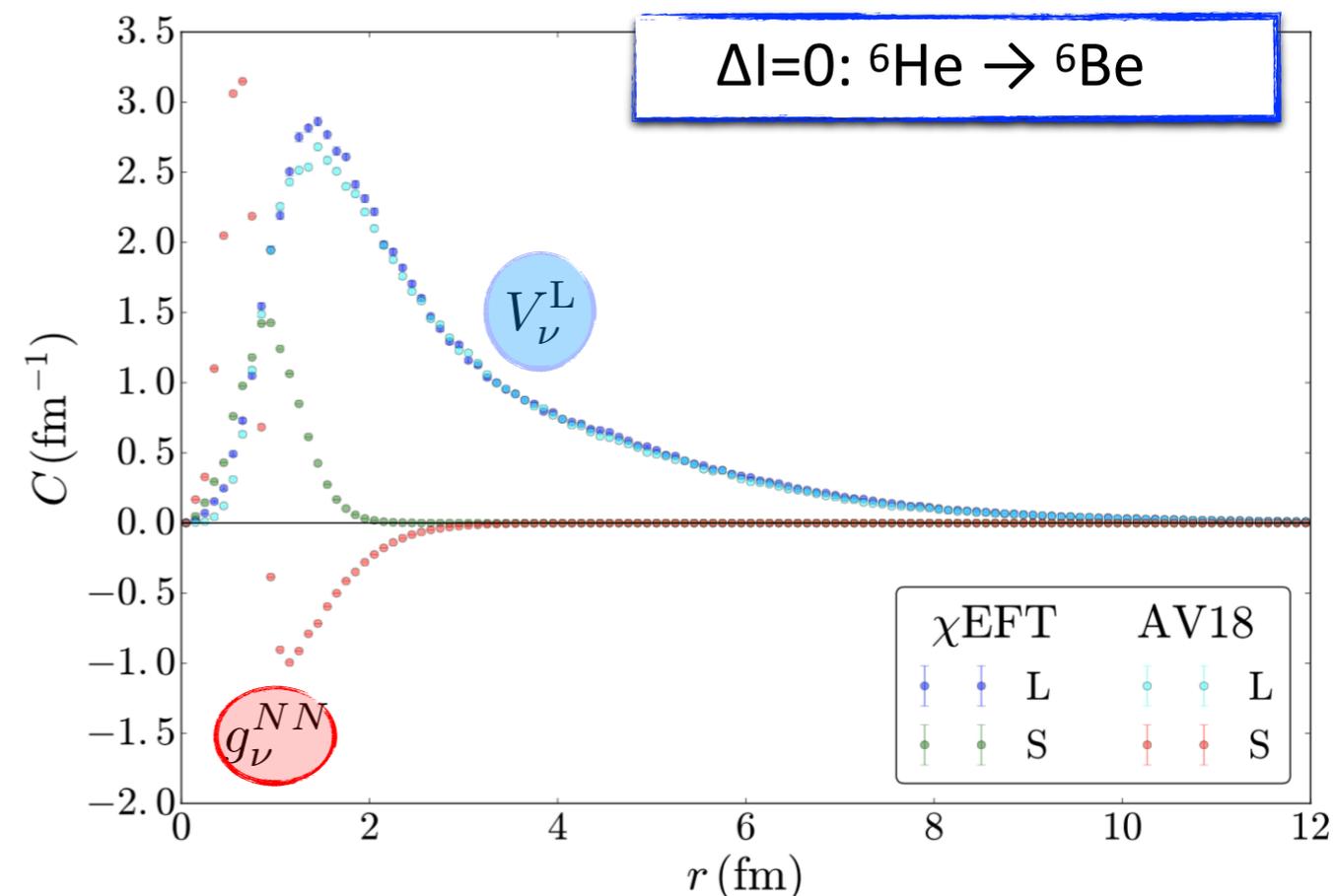
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  - Feature in realistic  $0\nu\beta\beta$  candidates



# Estimate of impact

## Light nuclei

M. Piarulli, R. Wiringa, S. Pastore

- Combine estimate

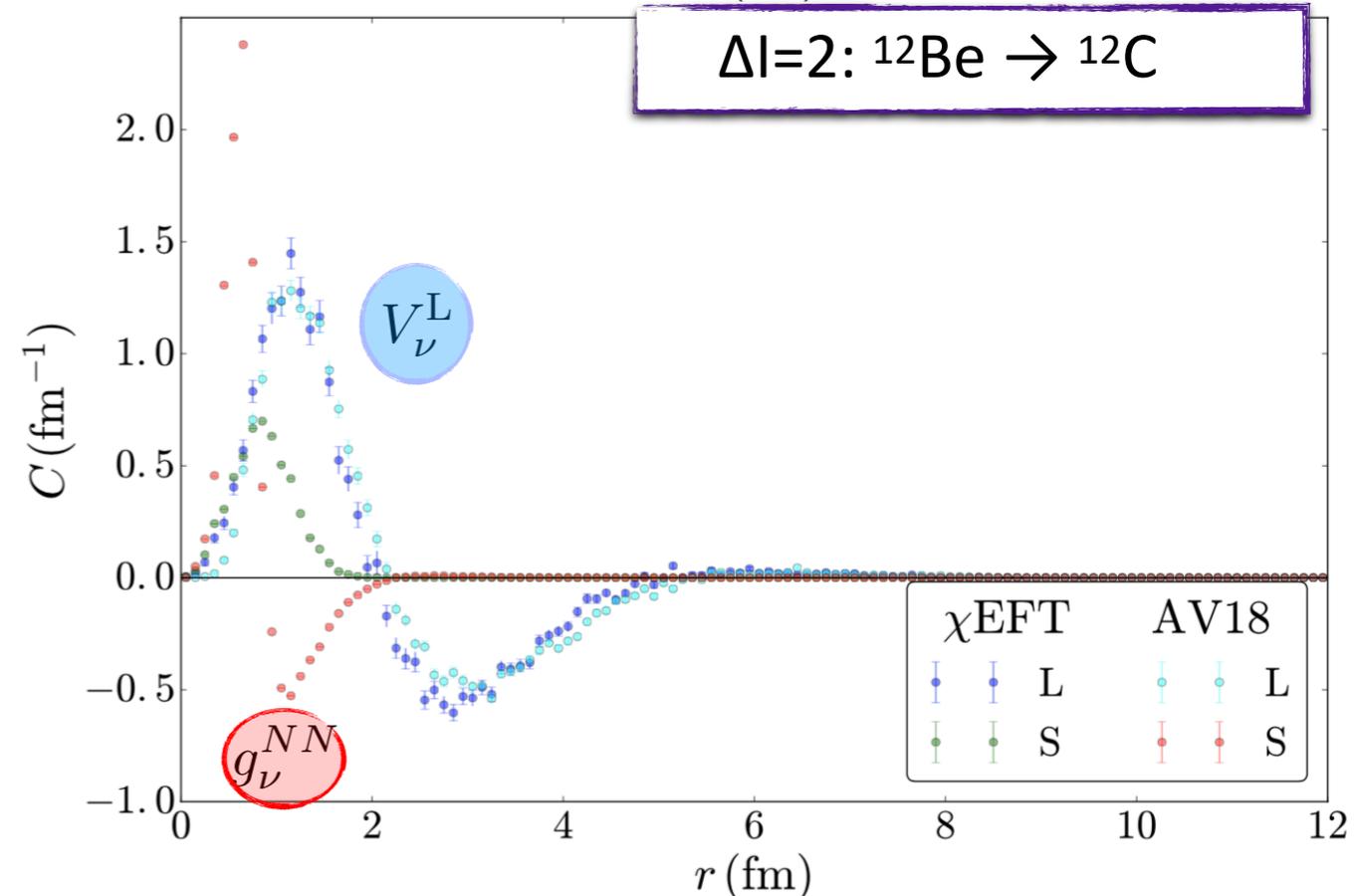
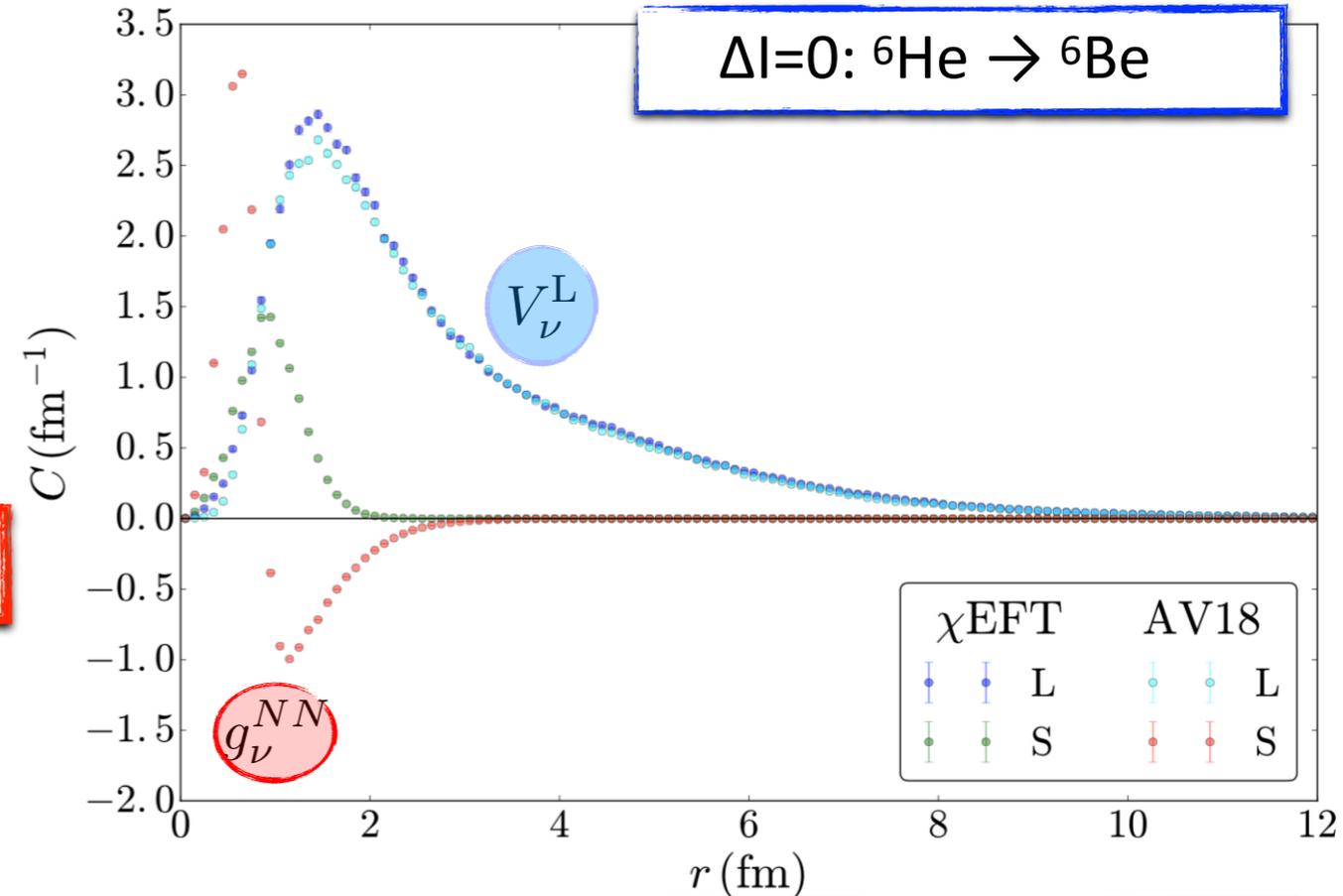
$$g_\nu = (C_1 + C_2)/2$$

Uncontrolled error

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# Example:

## The left-right model

# An example: LR model

## In Left-Right models:

- SM gauge symmetry is extended to  $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$
- Allows for parity or charge-conjugation to be restored at high energies
- Explains neutrino masses through the see-saw mechanism (Type-I & Type-II)

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- Right-handed bosons  $W_R, Z_R$
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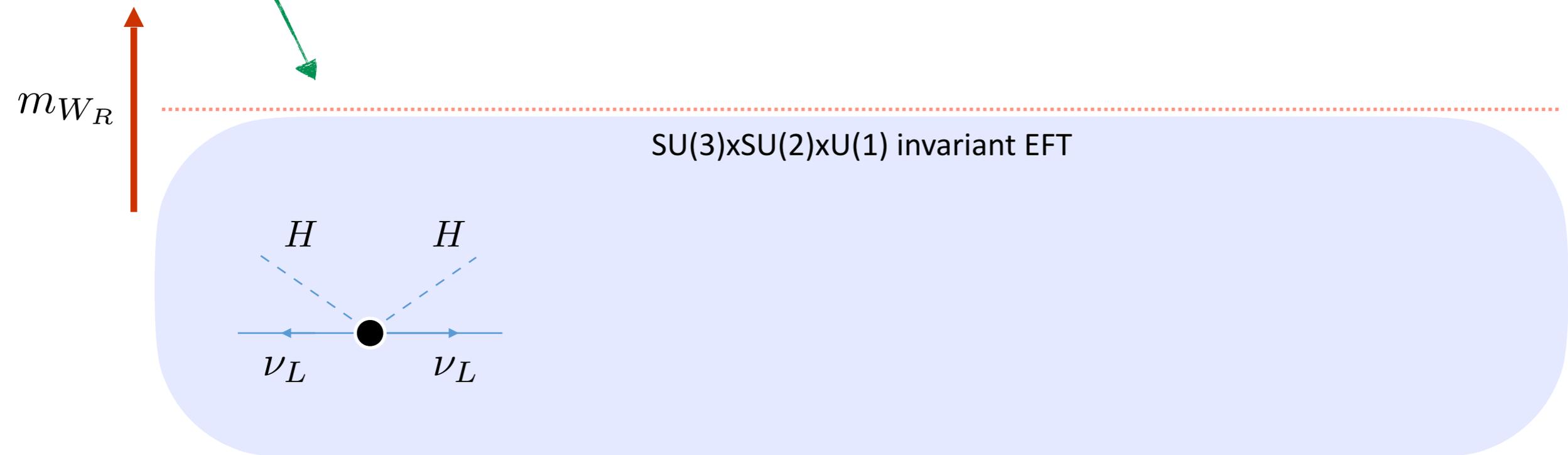
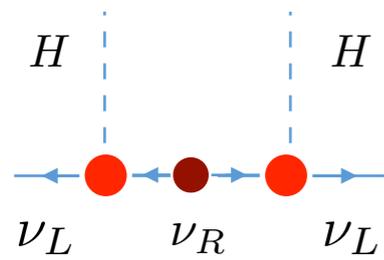
Violates lepton number

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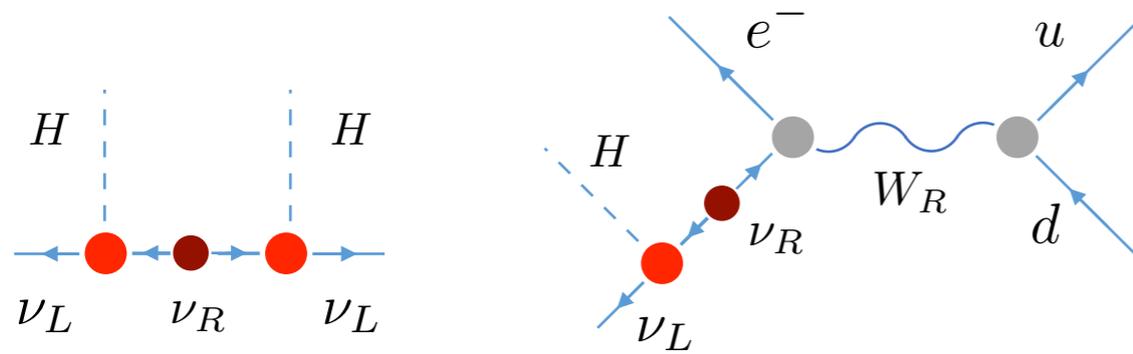
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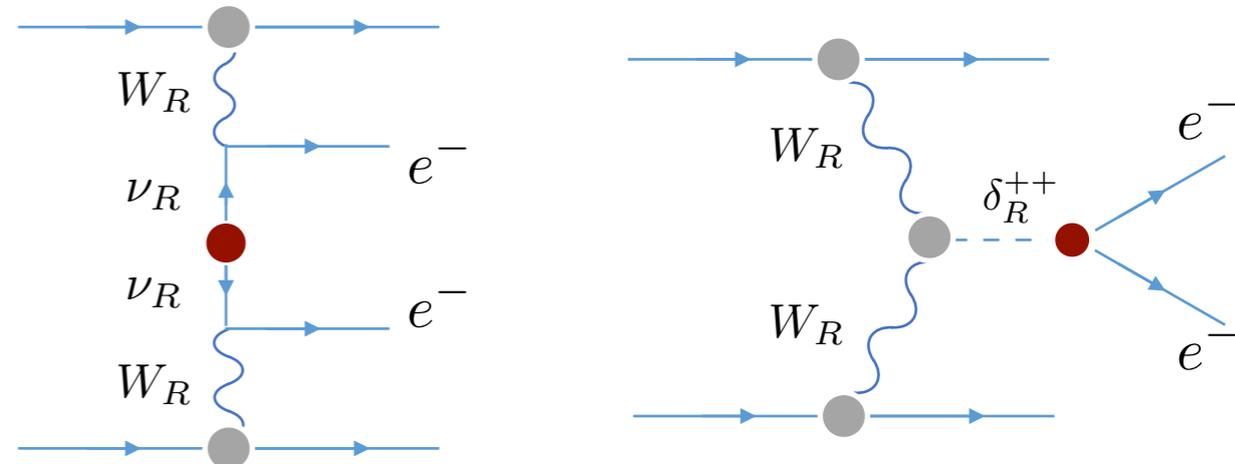
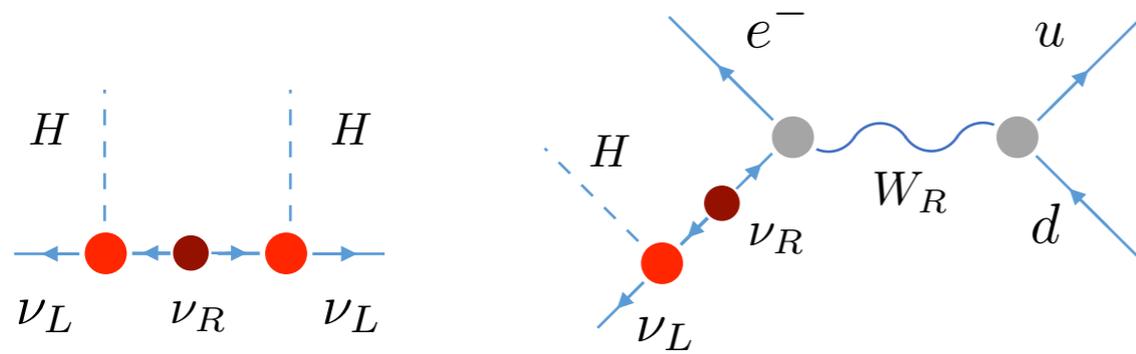
$m_{W_R}$

SU(3)xSU(2)xU(1) invariant EFT



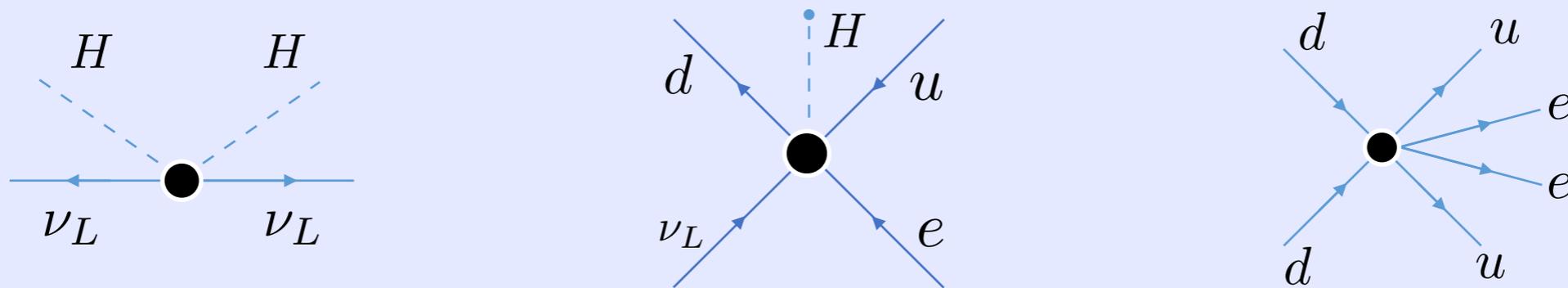
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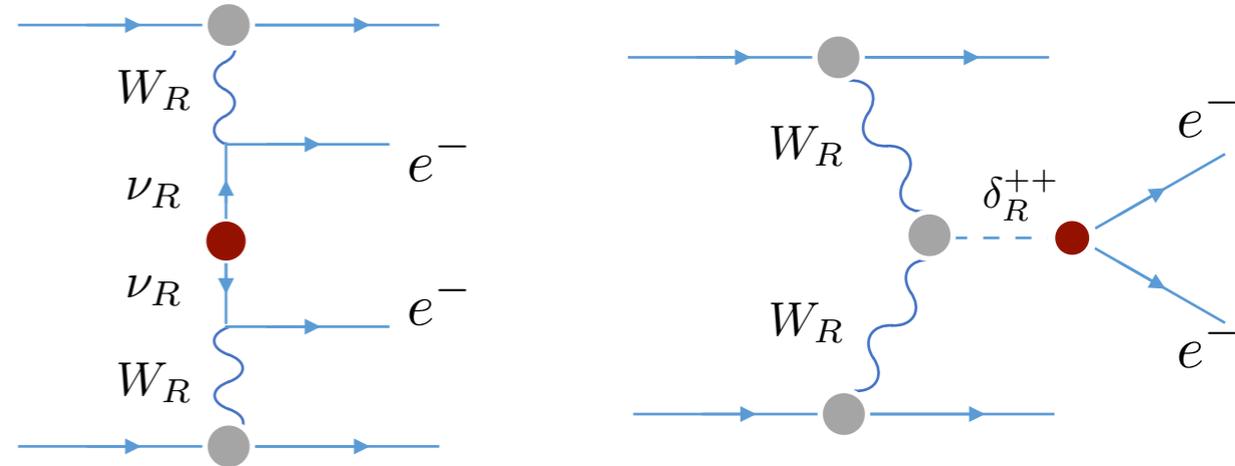
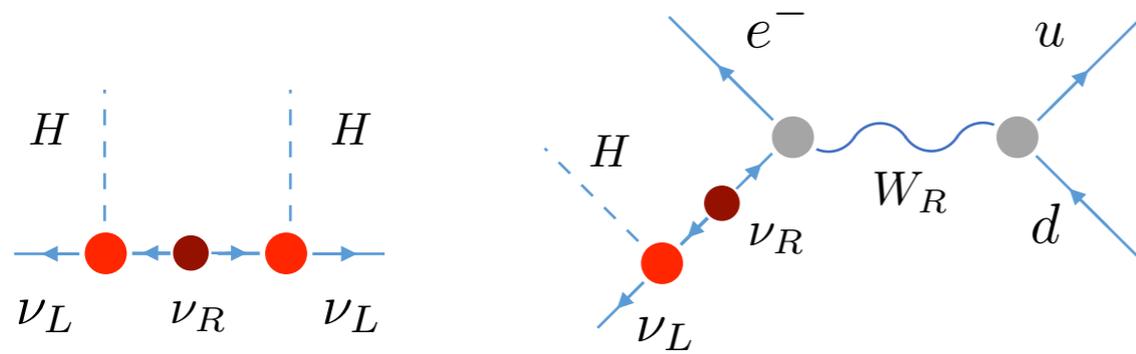
$m_{W_R}$  ↑

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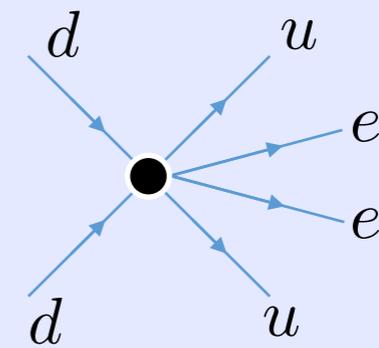
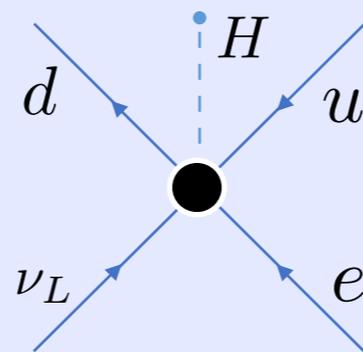
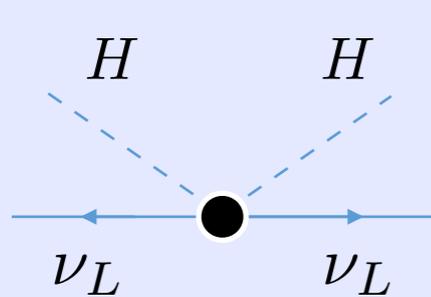
# An example: LR model

- $\sim y_e = m_e/v$
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$m_{W_R}$  ↑

SU(3)xSU(2)xU(1) invariant EFT



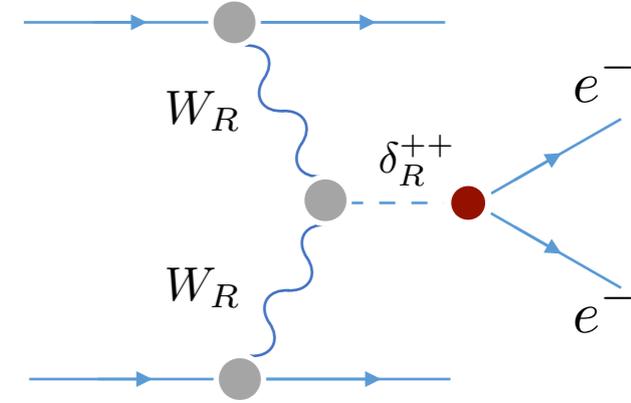
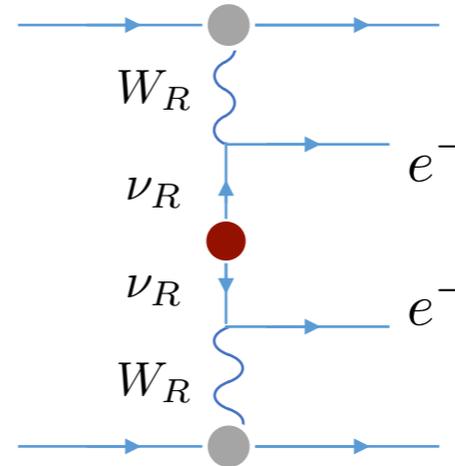
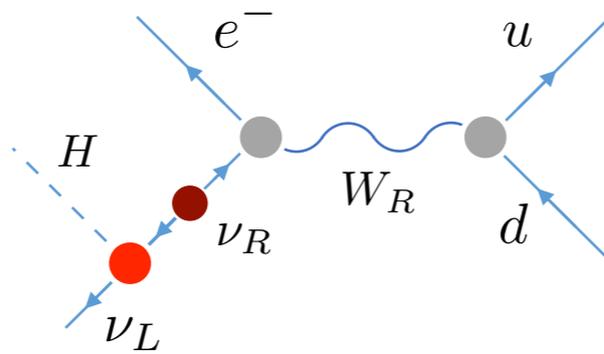
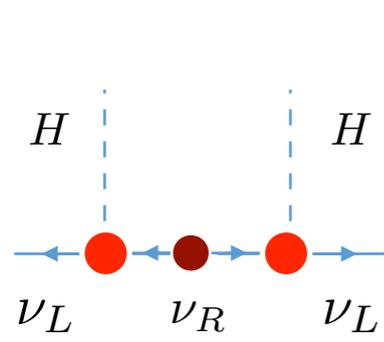
dim-5  $\sim y_e^2 \left(\frac{v}{\Lambda}\right)$

dim-7  $\sim y_e \left(\frac{v}{\Lambda}\right)^3$

Dim-9  $\sim \left(\frac{v}{\Lambda}\right)^5$

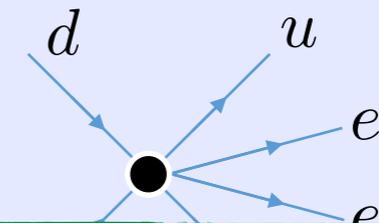
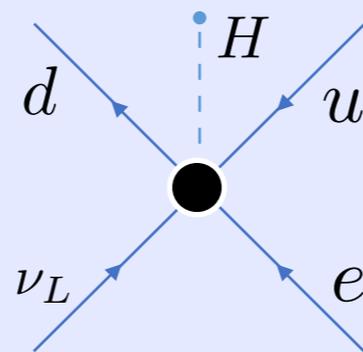
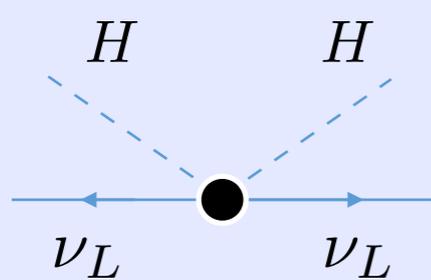
# An example: LR model

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$m_{W_R}$

SU(3)xSU(2)xU(1) invariant EFT



Framework captures all terms  
*Naively* of similar size for  $\Lambda=1-10$  TeV

dim-5  $\sim y_e^2 \left(\frac{v}{\Lambda}\right)$

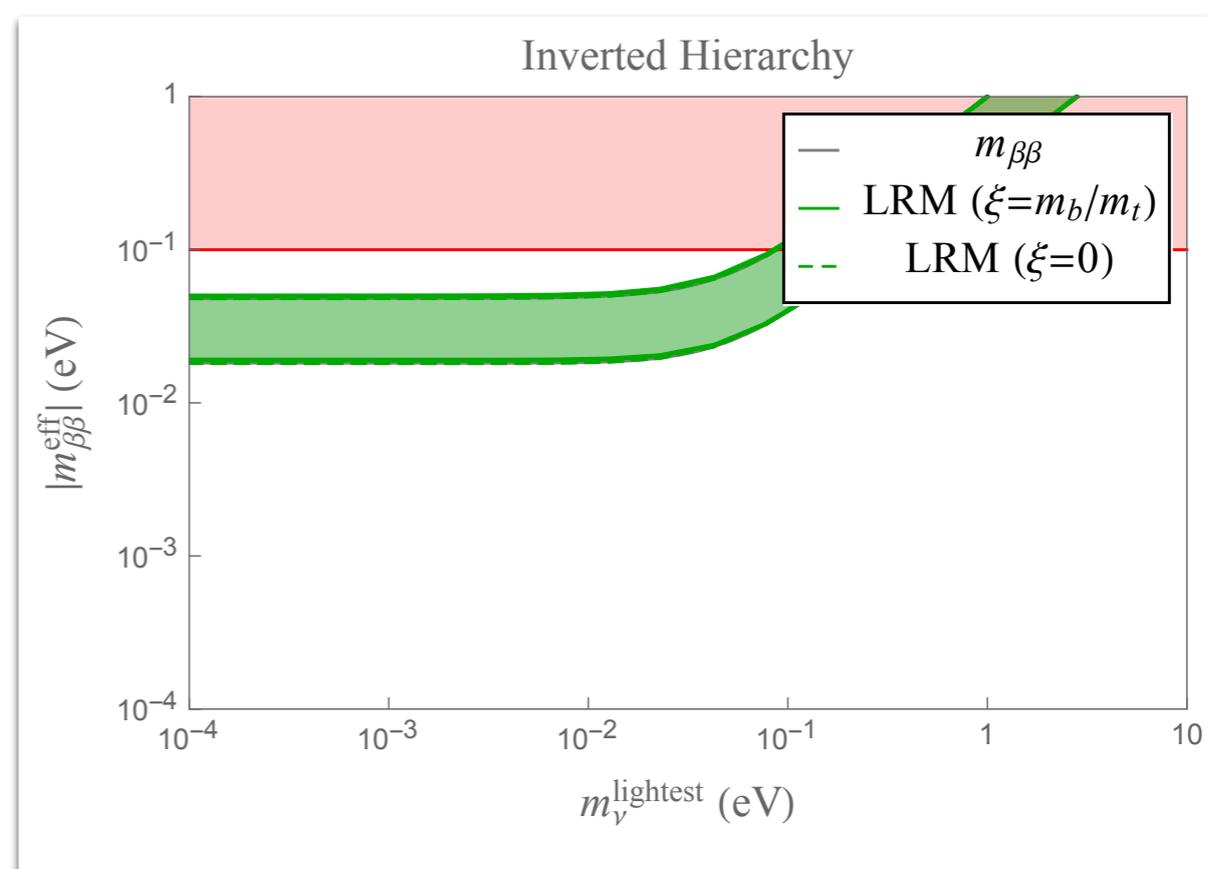
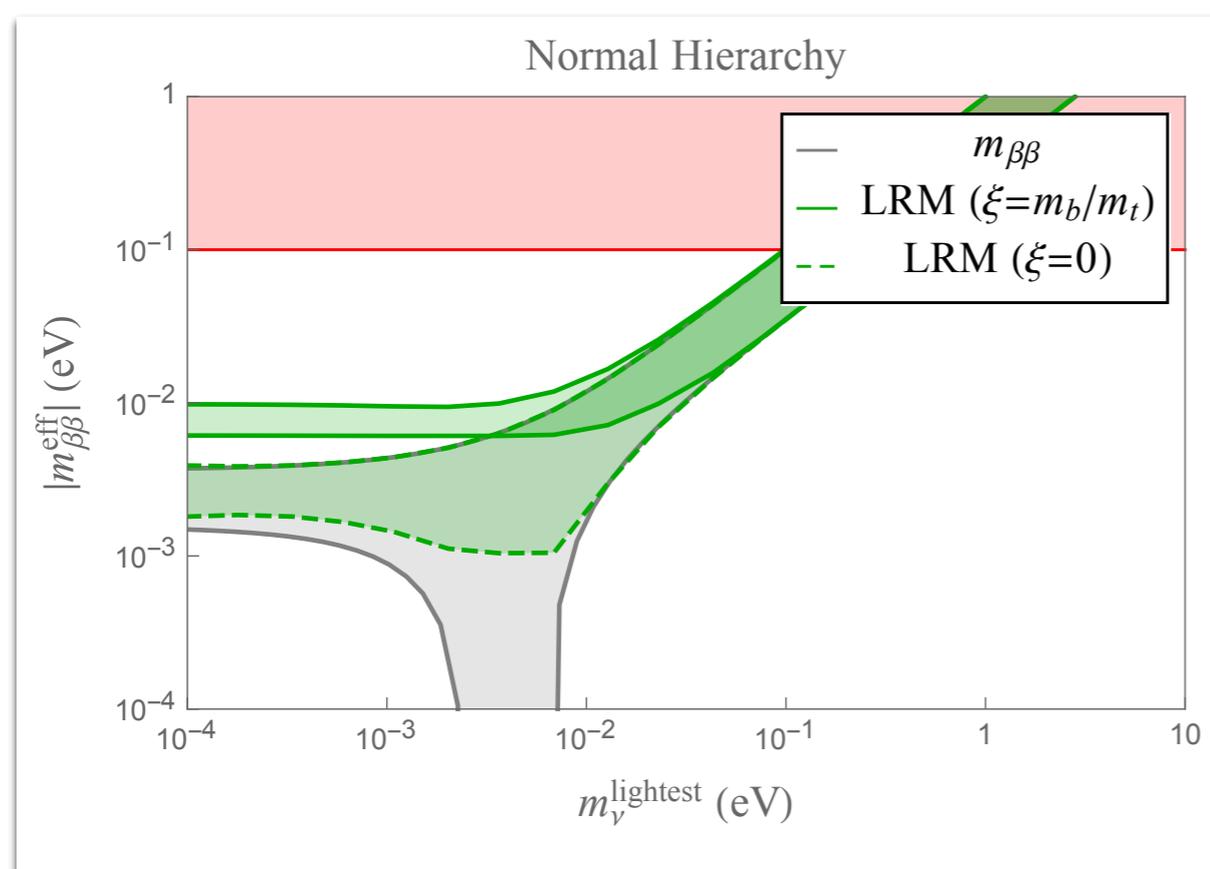
dim-7  $\sim y_e \left(\frac{v}{\Lambda}\right)^3$

Dim-9  $\sim \left(\frac{v}{\Lambda}\right)^5$

# An example: LR model

$$m_{W_R} = 4.5 \text{ TeV}, \quad m_{\nu_R} = 10 \text{ TeV}, \quad m_{\delta_R^{++}} = 4 \text{ TeV}$$

- Assume right-handed neutrino mixing follows the PMNS matrix



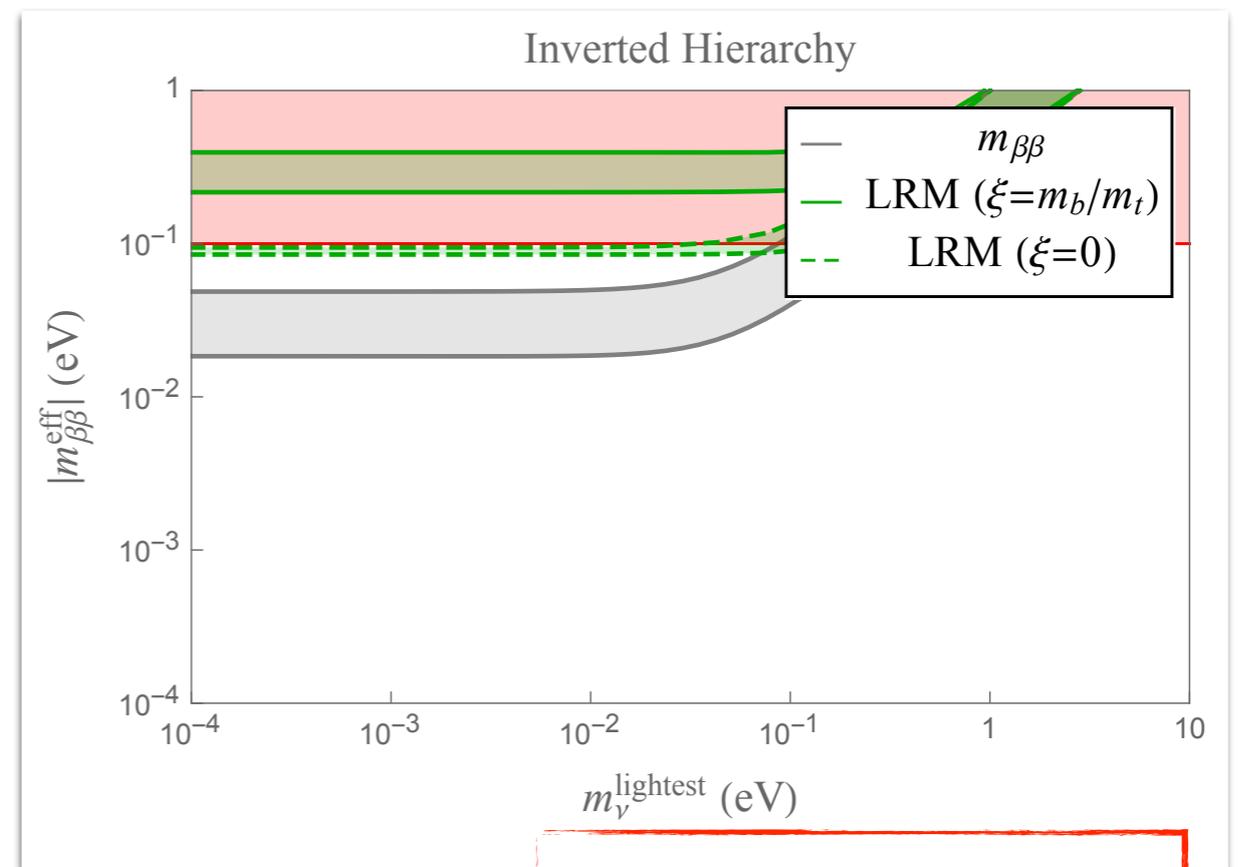
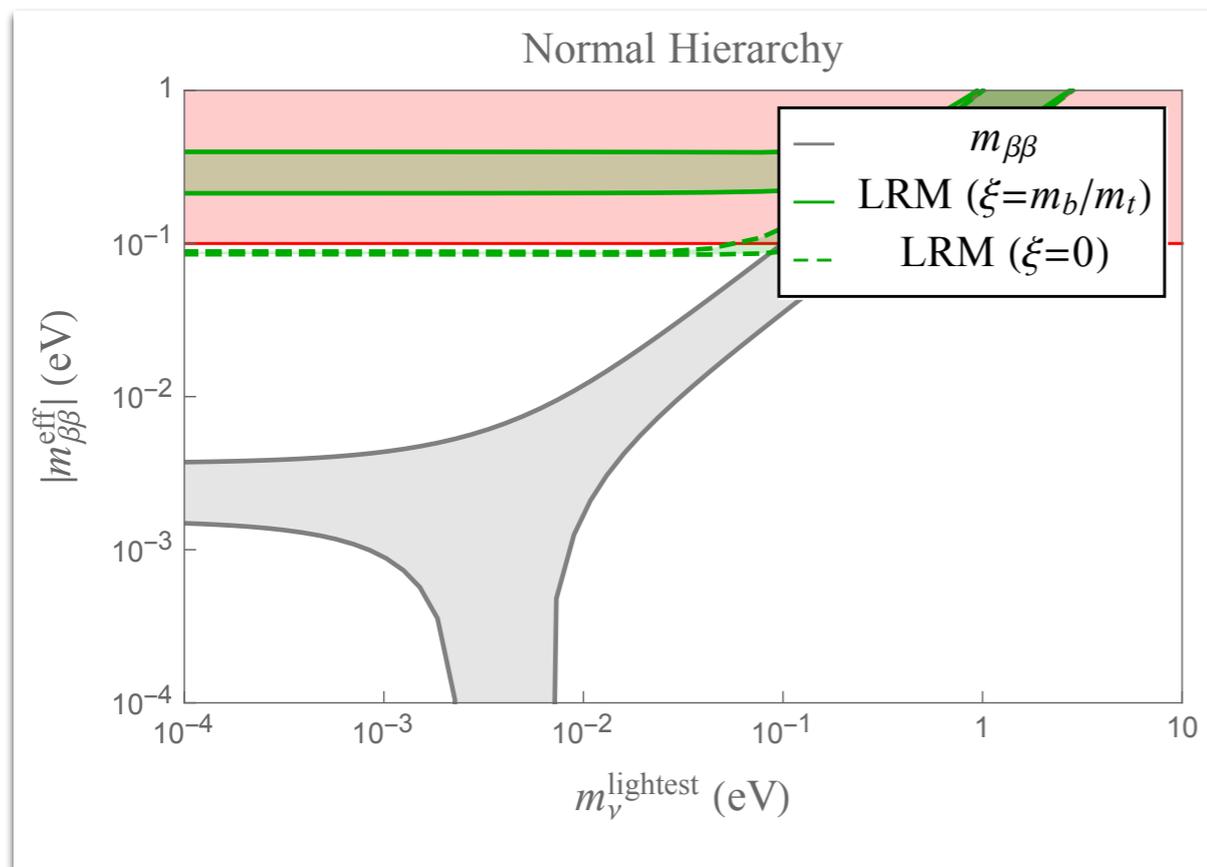
- Mild effect on NH (due to dim-9)
- Negligible effect in IH case, dim-5 terms dominate
  - Due to chiral suppression of the induced dim-6,7,9 operators

# An example: LR model

Not excluded by collider searches

$$m_{W_R} = 4.5 \text{ TeV}, \quad m_{\nu_R} = 10 \text{ GeV}, \quad m_{\delta_R^{++}} = 4 \text{ TeV}$$

- Assume right-handed neutrino mixing follows the PMNS matrix



- Large effect in both NH & IH
- Now dominated by dim-9 terms

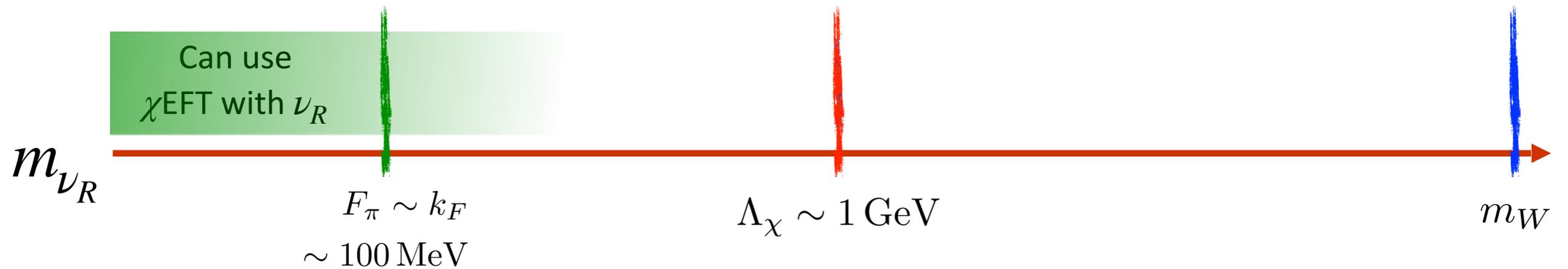
Subject to  
NME / LEC uncertainties

# Sterile neutrinos

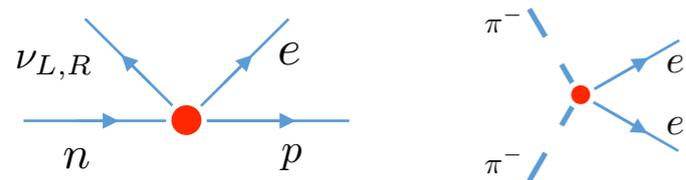
$m_{\nu_R}$  dependence

# Sterile neutrinos

$m_{\nu_R}$  dependence

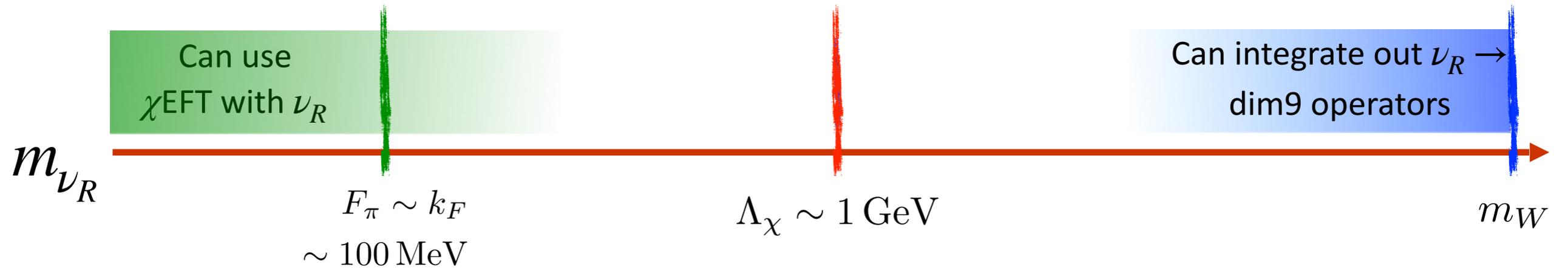


- Chiral EFT involving  $\nu_R$

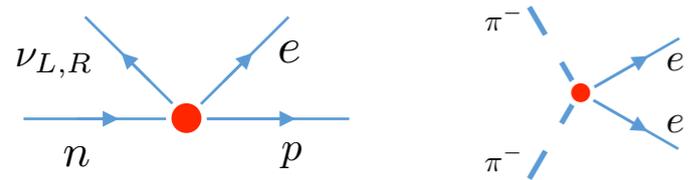


# Sterile neutrinos

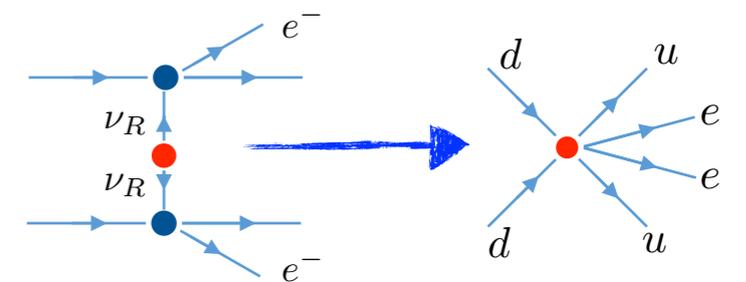
$m_{\nu_R}$  dependence



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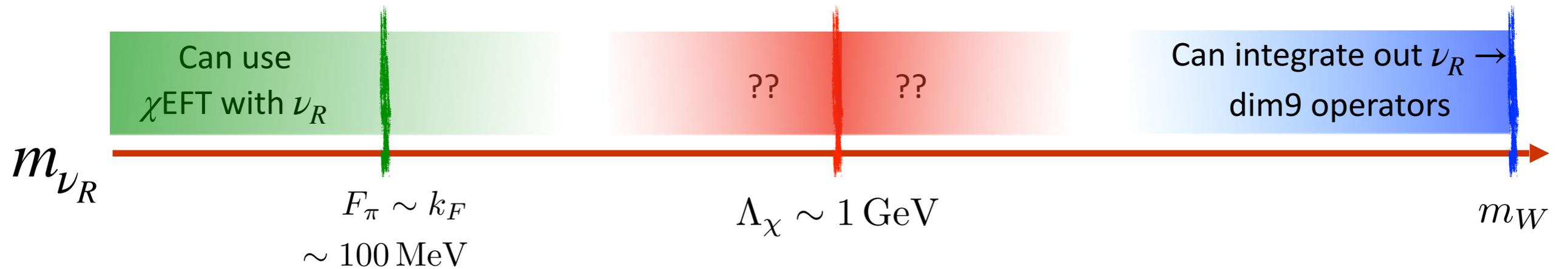
- Integrate out  $\nu_R$



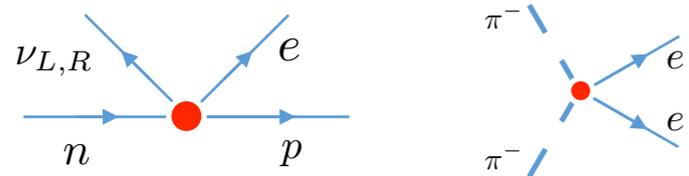
$\rightarrow$  Chiral EFT without  $\nu_R$

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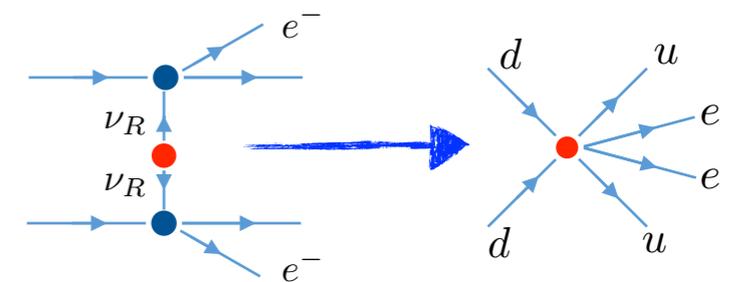
- Chiral EFT involving  $\nu_R$



- Neither EFT works well here

- Missing operators  $\sim \Lambda_{\chi}/m_{\nu_R}$
- Loop corrections  $\sim m_{\nu_R}/\Lambda_{\chi}$

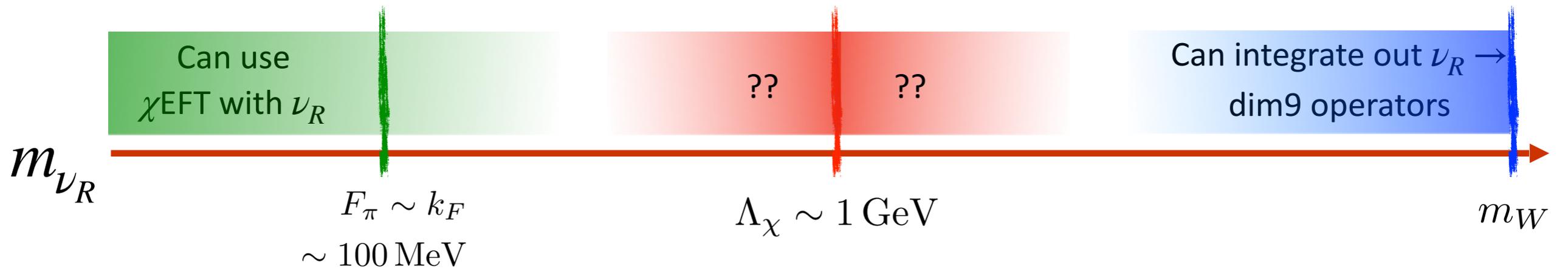
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# Sterile neutrinos

$m_{\nu_R}$  dependence



- Chiral EFT involving  $\nu_R$

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Interpolate

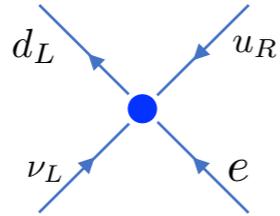
# Low energy constants

# LECs

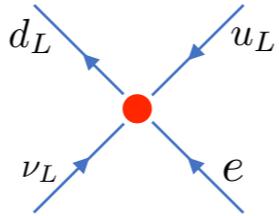
## Dimension 6

## Dimension 7

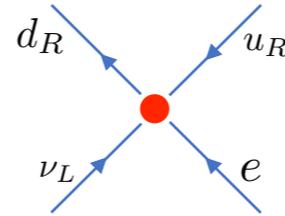
$$C_{SL,SR}^{(6)}$$



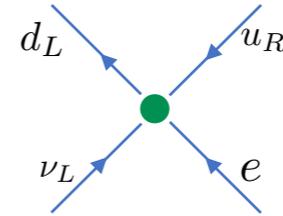
$$C_{VL}^{(6)}$$



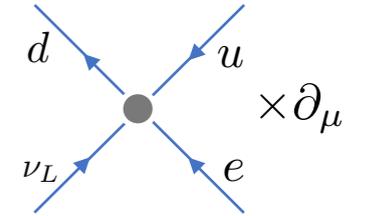
$$C_{VR}^{(6)}$$



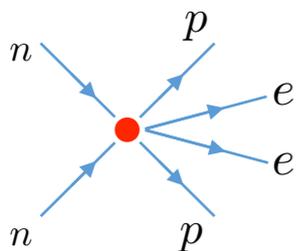
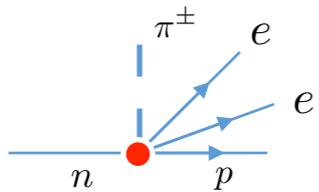
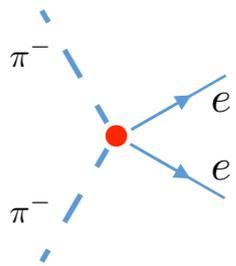
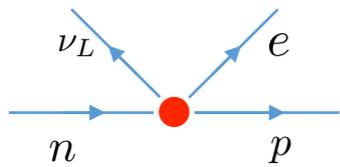
$$C_T^{(6)}$$



$$C_{VL,VR}^{(7)} \times \partial_\mu$$



Low energy constants



Quark  
condensate

Nucleon  
charges

Nucleon  
charges

Tensor  
charge

Quark  
condensate

NLO  
LEC

x1

x1

x1

x1

x2

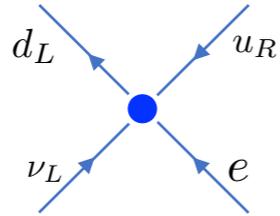
x1

# LECs

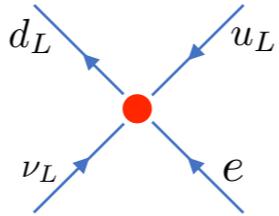
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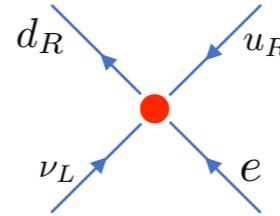
$$C_{SL,SR}^{(6)}$$



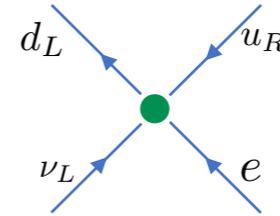
$$C_{VL}^{(6)}$$



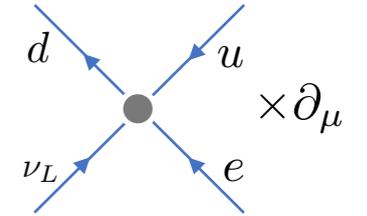
$$C_{VR}^{(6)}$$



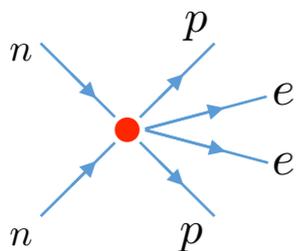
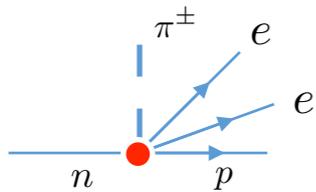
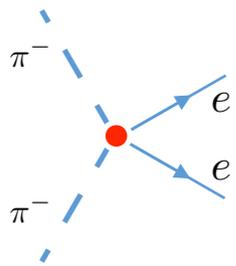
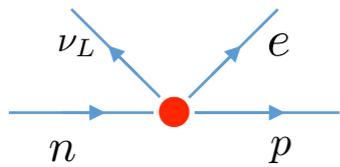
$$C_T^{(6)}$$



$$C_{VL,VR}^{(7)} \times \partial_\mu$$



Low energy constants



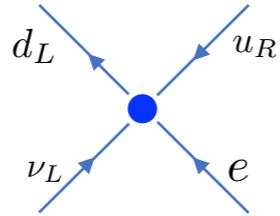
	Quark condensate  LQCD	Nucleon charges  expt	Nucleon charges  expt	Tensor charge  LQCD	Quark condensate  LQCD
				NLO LEC	
				x1	
	x1			x1	
	x1	x2		x1	

# LECs

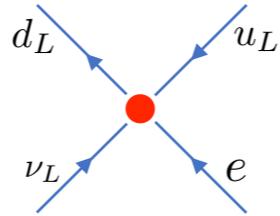
## Dimension 6

## Dimension 7

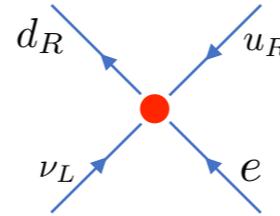
$$C_{SL,SR}^{(6)}$$



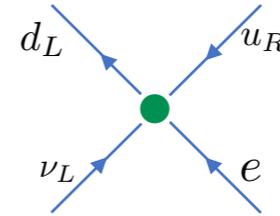
$$C_{VL}^{(6)}$$



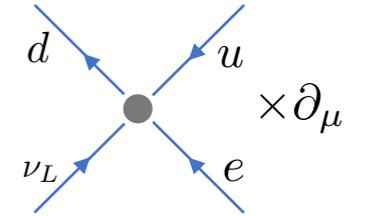
$$C_{VR}^{(6)}$$



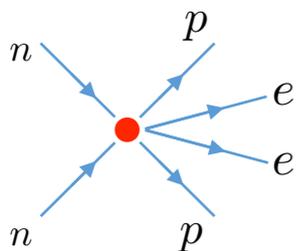
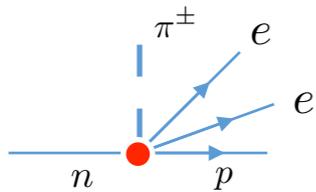
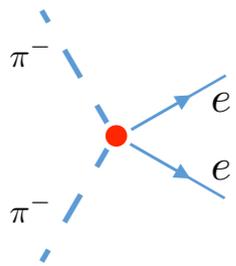
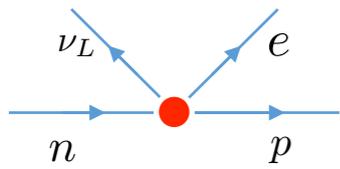
$$C_T^{(6)}$$



$$C_{VL,VR}^{(7)} \times \partial_\mu$$

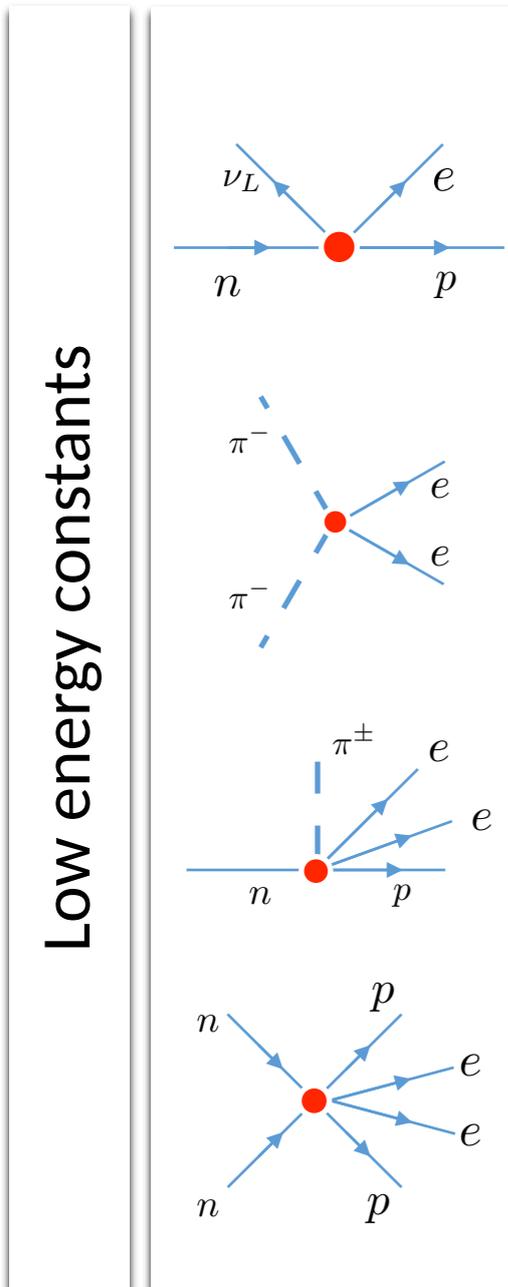
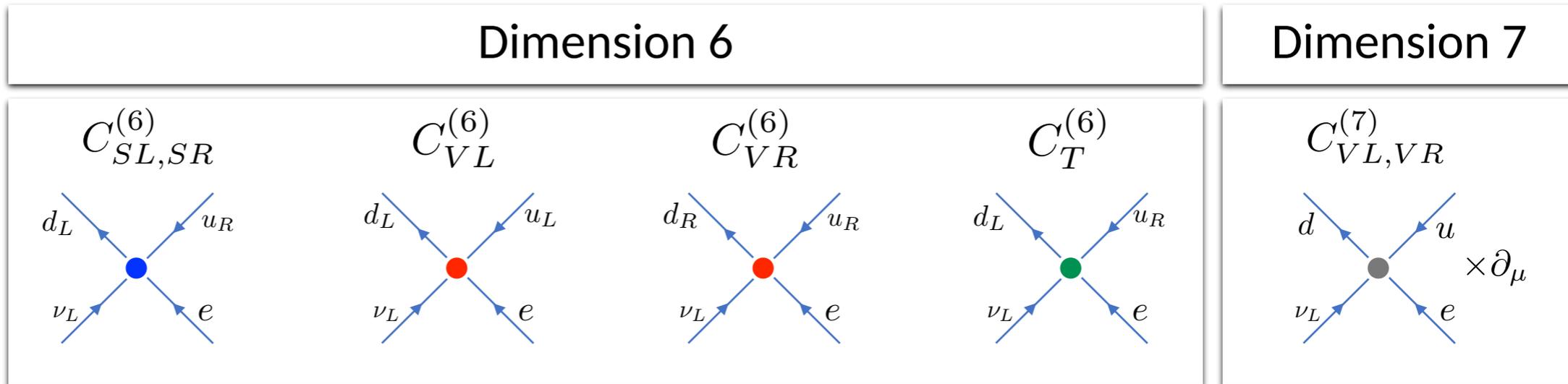


Low energy constants



Quark condensate  LQCD	Nucleon charges  expt	Nucleon charges  expt	Tensor charge  LQCD	Quark condensate  LQCD
			NLO LEC	
			x1	
	x1		x1	
	x1	x2	x1	

# LECs

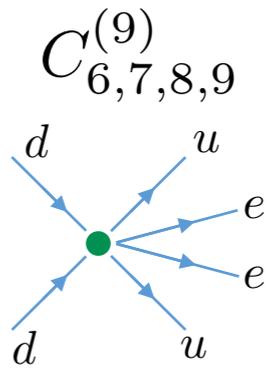
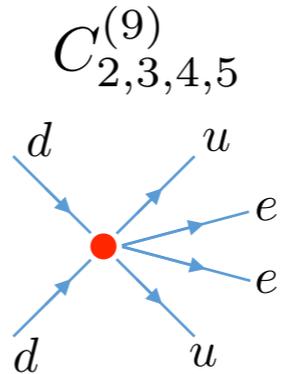
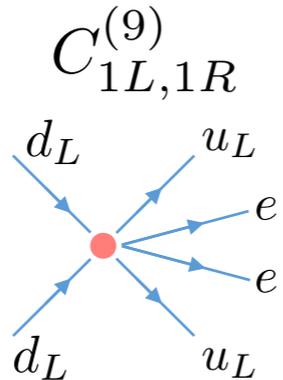


Quark condensate LQCD	Nucleon charges expt	Nucleon charges expt	Tensor charge LQCD	Quark condensate LQCD
			NLO LEC	
			x1	
	x1		x1	
	x1	Non-NDA	x1	
		x2		

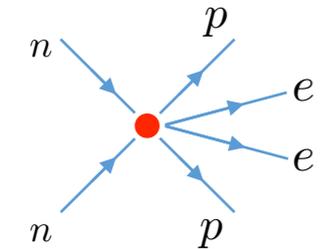
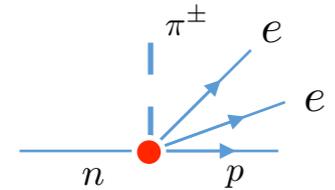
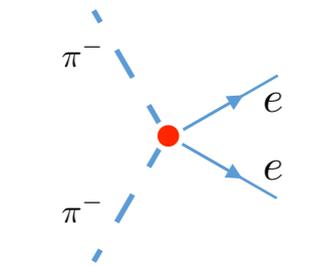
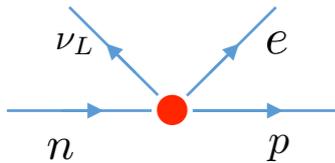
# LECs

## Dimension 9 - scalar

## Dimension 9 - vector



Low energy constants

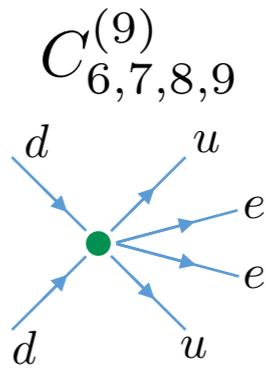
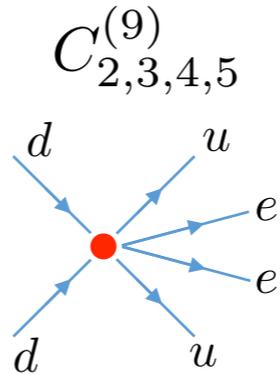
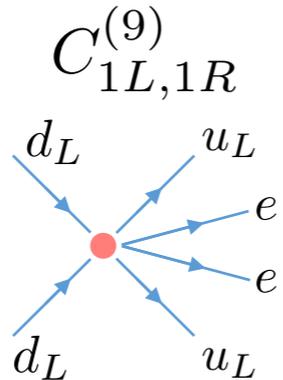


x1	x4		
x1		x2	
x1	x4		x2

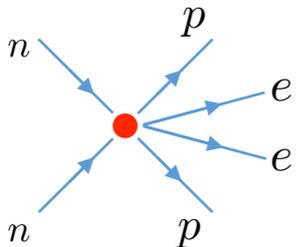
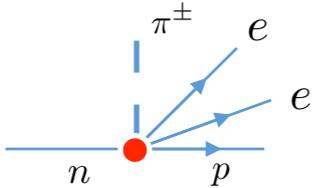
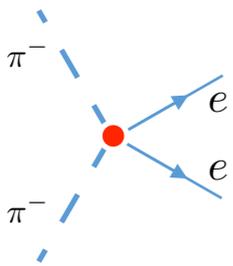
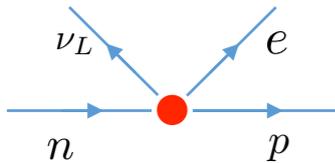
# LECs

Dimension 9 - scalar

Dimension 9 - vector



Low energy constants

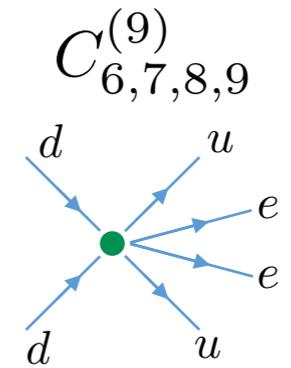
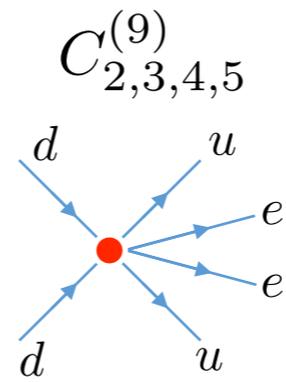
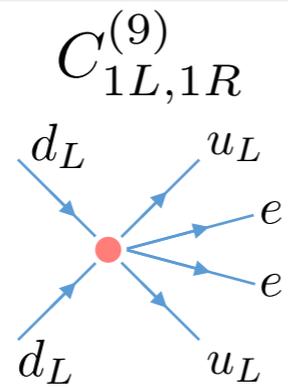


x1 ✓ LQCD	x4 ✓ LQCD		
x1			x2
x1	x4		x2

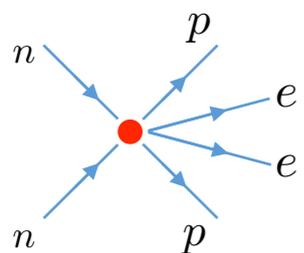
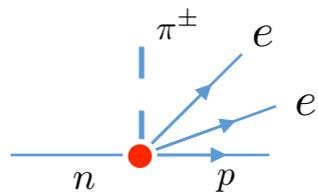
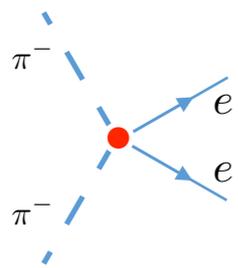
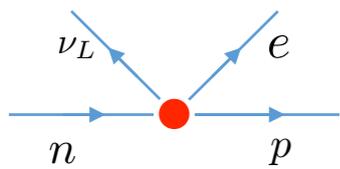
# LECs

Dimension 9 - scalar

Dimension 9 - vector



Low energy constants

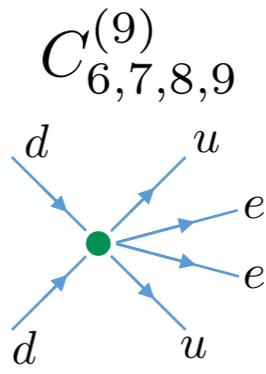
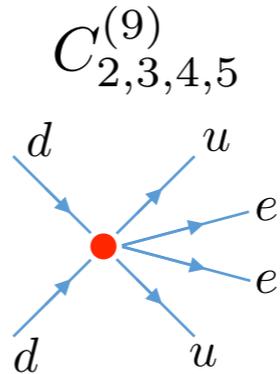
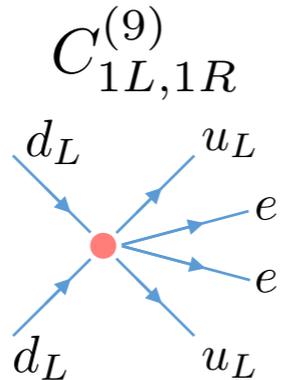


	$x1$ ✓ LQCD	$x4$ ✓ LQCD	
	$x1$ ✗		$x2$ ✗
	$x1$ ✗	$x4$ ✗	$x2$ ✗

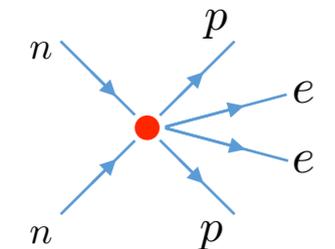
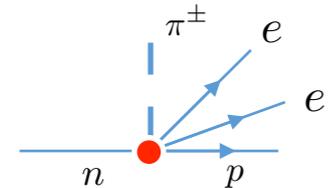
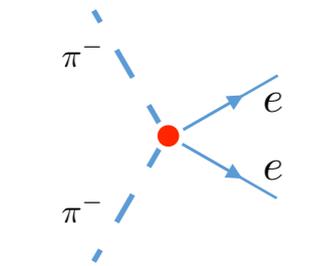
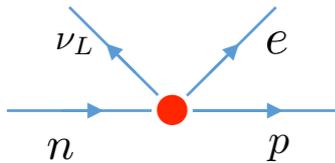
# LECs

Dimension 9 - scalar

Dimension 9 - vector



Low energy constants



	$x1$ ✓ LQCD	$x4$ ✓ LQCD	
	$x1$ ✗		$x2$ ✗
	$x1$ ✗	Non-NDA	
	$x1$ ✗	$x4$ ✗	$x2$ ✗